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STUDY OF POTENTIAL FOR MOTOR VEHICLE FUEL ECONOMY IMPROVEMENT

TRUCK AND BUS PANEL REPORT NO. 7

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16. Abstract

This Truck and Bus Panel Report is Number Seven (7) of a group of seven (7) prepared by special panels of the Task Force established under the joint chairmanship of DOT and EPA to conduct a study of the practicability of a fuel economy improvement standard of 20% for new motor vehicles produced in the 1980 time frame.

Special consideration is given in this report to the potential improvement of truck and bus fuel economy implementable by the 1980 production year. Vehicles considered in the section are those with gross vehicle weight ratings of 10,000 pounds or more. This group of vehicles presently consume an estimated 18% of all highway fuel, but the technologies and production facilities involved in efforts to improve the fuel consumption of this category of vehicles are quite different from those of the automobile.

Analyses of available data indicate fuel economy improvements for some individual trucks can be as great as 41% by the 1980 production year. Assessment of such technology applied without cost or production capacity restraint would yield an aggregate reduction of 25% in the fuel consumed by the new trucks and buses manufactured in 1980

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PREFACE

This Truck and Bus Panel Report is Number Seven (7) of a group of seven (7) prepared by special panels of the Task Force established under the joint chairmanship of DOT and EPA to conduct a study of the practicability of a fuel economy improvement standard of 20% for new motor vehicles produced in the 1980 time frame. Each panel addressed a major impact area and drew on a variety of sources in preparing its report, including previous DOT and EPA research, and industry and public comments.

Materials developed by the various study panels were used in preparing the Report to Congress entitled "Potential for Motor Vehicle Fuel Economy Improvement", dated 24 October 1974 (second printing, 18 November 1974). Assumptions and conclusions expressed in the panel reports, however, are those of the respective panels and do not necessarily reflect official positions or policies of the U.S. Department of Transportation, the U.S. Environmental Protection Agency, or the study Task Force.

The complete Panel Reports set consists of the following:

Report No. 1: Policy Assessment Panel Report
Report No. 2: Safety Implications Panel Report
Report No. 3: Air Quality and Emissions Panel Report
Report No. 4: Technology Panel Report
Report No. 5: Economics Panel Report
Report No. 6: Fuel Economy Test Procedures Panel Report
Report No. 7: Truck and Bus Panel Report

TABLE OF CONTENTS

Section			Page
1.	INTRODUCTION		1
2.	SUMMARY		3
3.	TECHNICAL DISCUSSION		5
	3.1	SUBJECT VEHICLES, 1973 DATA BASE AND 1980 PROJECTIONS	5
		3.1.1 New Truck Registration Versus Driving Mode	13
		3.1.2 New Truck Fuel Consumption Versus Driving Mode	15
		3.1.3 Selection of Reference Vehicles	18
		3.1.4 Projections of 1980 New Truck and Bus Registrations	18
	3.2	FUEL ECONOMY MEASUREMENT	21
		3.2.1 Elements of a Fuel Economy Measurement Technique	21
		3.2.2 Existing Practices for Fuel Economy Measurement	22
		3.2.3 Areas of Future Development	27
		3.2.4 Appropriate Measurement Units	28
		3.2.5 Regulatory Considerations	30
	3.3	IMPROVEMENT OPTIONS	30
		3.3.1 Diesel Engines	31
		3.3.1.1 Diesel Substituted for Gasoline Engines	31
		3.3.1.2 Turbocharging a Diesel	36
		3.3.1.3 Derated Horsepower	39
		3.3.1.4 Reducing Engine RPM	41
		3.3.2 Gasoline Fueled Engines (Spark Ignition)	43
		3.3.2.1 Lean Burn	43
		3.3.2.2 Fuel Injection	47
		3.3.2.3 Turbocharging	50
		3.3.2.4 Stratified Charge Engine Substituted for Gasoline Engine	57
		3.3.2.5 Summary of Spark Ignition Engine Improvements	58

Preceding page blank

TABLE OF CONTENTS (CONT)

Section		Page
3.3.3	Optimized Cooling Systems Using Modulating Fans	60
3.3.4	Power Train	64
3.3.4.1	Improved Transmissions; Automatic, Manual and Continuously Variable (CVT)	65
3.3.4.2	Lower Axle Ratio	67
3.3.4.3	Tag Axle	70
3.3.4.4	Substitution of Radial Tires for Bias Ply Tires	73
3.3.5	Optimized Aerodynamics	76
3.3.6	Weight and Size Optimizations	81
3.3.6.1	Relationship between Fuel Productivity and Vehicle Size and Weight	81
3.3.6.2	Effect of Changing Tare Weight	85
3.3.7	The Effect of Highway Speed	87
3.4	EMISSION IMPACT	89
3.4.1	Diesel Engine Substitution	90
3.4.2	Turbocharging Diesel Engines	91
3.4.3	Other Engine Technology Options	92
3.4.4	Future Emissions Standards	93
3.5	FUEL ECONOMY IMPROVEMENTS	95
3.5.1	Method of Analysis	95
3.5.2	Synthesized Vehicle Description and Fuel Economy Improvements	98
REFERENCES		103

LIST OF FIGURES

Figure		Page
3-1	New Truck and Bus Registrations, 1973 Calendar Year, by Weight Class and Driving Mode.....	16
3-2	Truck and Bus Fuel Consumption by Weight Class and Driving Mode for 1973 Calendar year.....	17
3-3	Gasoline and Diesel Truck Road Route Fuel Economy.....	34
3-4	Rolling Resistance Comparison for Different Types of Tires.....	74
3-5	Variation of Fuel Productivity with Changes in Payload as Influenced by Vehicle Weight.....	82
3-6	Power Required for a Typical Tractor - Trailer Combination.....	88

LIST OF TABLES

Table		Page
3-1	VARIATIONS AVAILABLE FOR EACH COMPONENT	6
3-2	MEDIUM DUTY TRUCK FUEL CONSUMPTION	9
3-3	LIGHT HEAVY DUTY TRUCK FUEL CONSUMPTION	10
3-4	HEAVY DUTY TRUCK FUEL CONSUMPTION	11
3-5	BUS FUEL CONSUMPTION	13
3-6	1973 NEW TRUCK AND BUS REGISTRATIONS BY WEIGHT CLASS, DUTY MODE AND POWER PLANT	19
3-7	PROJECTIONS FOR 1980 - NEW TRUCK AND BUS REGISTRATION BY WEIGHT CLASS, DUTY MODE AND POWER PLANT	20
3-8	FUEL ECONOMY IMPROVEMENT ESTIMATES DIESEL ENGINE SUBSTITUTION FOR GASOLINE ENGINE	33
3-9	DIESEL ENGINE SUBSTITUTION COSTS	35
3-10	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM SUBSTITUTING A DIESEL ENGINE FOR A GASOLINE ENGINE	37
3-11	FUEL ECONOMY IMPROVEMENT (%) BY TURBOCHARGING A DIESEL ENGINE	38
3-12	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM TURBO-CHARGING DIESEL ENGINES	40
3-13	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM DERATED DIESEL ENGINES	42
3-14	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM REDUCED DIESEL ENGINE SPEED	44
3-15	IMPROVEMENT IN GASOLINE ENGINE FUEL ECONOMY (%) WITH LEAN BURN CONCEPTS	46
3-16	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS FOR LEAN BURN-GASOLINE ENGINES	48
3-17	COMPARISON OF FUEL ECONOMY IMPROVEMENT ESTIMATES FOR GASOLINE ENGINES WITH FUEL INJECTION	49
3-18	COMPARISON OF FUEL ECONOMY OF FUEL INJECTED VERSUS CARBURETED ENGINES	51

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LIST OF TABLES (CONT)

Table		Page
3-19	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM FUEL INJECTION-GASOLINE ENGINE	52
3-20	PERCENT IMPROVEMENT FOR TURBOCHARGED GASOLINE ENGINE OVER NATURALLY ASPIRATED GASOLINE ENGINES	54
3-21	COMPARISON OF EMISSIONS OF TURBOCHARGED AND NON-TURBOCHARGED GASOLINE ENGINES ON 13-MODE CYCLE	55
3-22	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM TURBOCHARGING GASOLINE ENGINES	56
3-23	FUEL ECONOMY IMPROVEMENT RESULTING FROM STRATIFIED CHARGING GASOLINE ENGINE	59
3-24	FUEL ECONOMY IMPROVEMENT RESULTING FROM AN OPTIMIZED COOLING SYSTEM	63
3-25	ASSESSMENT OF POSSIBLE FUEL ECONOMY IMPROVEMENT BY SUBSTITUTING IMPROVED TRANSMISSIONS FOR CONVENTIONAL TRANSMISSIONS	66
3-26	BUS FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM THE SUBSTITUTION OF AN AUTOMATIC FOUR SPEED TRANSMISSION WITH LOCK-UP FOR A MANUAL TRANSMISSION	68
3-27	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM THE SUBSTITUTION OF A CONTINUOUSLY VARIABLE TRANSMISSION FOR A MANUAL TRANSMISSION	69
3-28	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM A LOWER AXLE RATIO	71
3-29	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS FROM A TAG AXLE ON CLASS VIII VEHICLES	72
3-30	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM THE USE OF RADIAL TIRES	77
3-31	FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM OPTIMIZING AERODYNAMICS	80
3-32	CHANGE IN FUEL PRODUCTIVITY AS A FUNCTION OF INCREASES IN WEIGHT AND VOLUME LIMITS	84

LIST OF TABLES (CONT)

Table		Page
3-33	CARRYING CAPACITIES AND FUEL USE FOR TYPICAL PRESENT AND PROPOSED VEHICLE COMBINATIONS	86
3-34	CHANGE IN FUEL PRODUCTIVITY AS A FUNCTION OF DECREASES IN TARE WEIGHT	87
3-35	EFFECT OF SPEED ON FUEL ECONOMY	90
3-36	AVERAGE MASS EMISSIONS ON THE SAN ANTONIO ROAD ROUTE	91
3-37	TURBOCHARGER EMISSIONS COMPARISON	92
3-38	HEAVY DUTY ENGINE EMISSION STANDARDS	94
3-39	ASSESSMENT OF FUEL ECONOMY IMPROVEMENTS FOR TRUCKS AND BUSES	96
3-40	FUEL ECONOMY IMPROVEMENT FOR CLASS VI SYNTHESIZED VEHICLE-LOCAL DRIVING MODE	99
3-41	FUEL ECONOMY IMPROVEMENT FOR CLASS VIII SYNTHESIZED VEHICLE WITH TURBOCHARGED DIESEL-LOCAL DRIVING MODE	100
3-42	FUEL ECONOMY IMPROVEMENT FOR CLASS VIII SYNTHESIZED VEHICLE WITH TURBOCHARGED DIESEL-SHORT DRIVING MODE	101
3-43	FUEL ECONOMY IMPROVEMENT FOR CLASS VII SYNTHESIZED VEHICLE WITH TURBOCHARGED DIESEL-LONG (INTERCITY) DRIVING MODE	102

1. INTRODUCTION

Special consideration is given in the following pages to the potential improvement of truck and bus fuel economy implementable by the 1980 production year. Vehicles considered in this section are those with gross vehicle weight ratings of 10,000 pounds or more. This group of vehicles presently consumes an estimated 18% of all highway fuel, but the technologies and production facilities involved in efforts to improve the fuel consumption of this category of vehicles are quite different from those of the automobile. As a supplement to the main body of the report to Congress required by Section 10 of the Energy Supply and Environmental Coordination Act of 1974 this report deals with: the special character of the subject vehicles and their uses; the peculiar problems of fuel economy measurements of trucks and buses; parametric assessment of potential fuel saving technologies; and an assessment of the aggregate benefits of the options available for the 1980 production year. In addition, discussions are provided of other factors influencing the achievement of a 20% improvement in fuel economy.

2. SUMMARY

Analyses of available data indicate fuel economy improvements for some individual trucks can be as great as 41% by the 1980 production year. Assessment of such technology applied without cost or production capacity restraint would yield an aggregate reduction of 25% in the fuel consumed by the new trucks and buses manufactured in 1980.

When considerations of cost benefit tradeoffs to the purchaser and production capacity by 1980 are taken into account, the maximum fuel savings for the new 1980 vehicles drops to 18%.

On a production weighted average basis, the potential 1980 new vehicle fuel economy improvement also appears to be 18% (based on assessment of four representative vehicles). More importantly, the 1980 local mission vehicles exhibit fuel economy improvement potential of only 14-17%, hence manufacturers with a preponderance of such vehicles would find it extremely difficult to comply with a legislated 20% fuel economy improvement. Manufacturers of intercity and transit buses would find it very difficult to achieve a 20% fuel economy improvement by 1980.

If on the other hand, weight, length and configuration limits imposed upon truck operations by federal and state law were unified and certain recommended changes were made, a reduction in heavy duty truck fuel consumption equivalant to that expected from advanced technology could be realized. Highway speed regulation was not considered as a variable from the base year to the 1980 production year, but if highway speeds were returned to pre-1974 levels, fuel economy would be decreased by 8% or more in long haul operations.

The analysis indicated the most significant payoff technology options to be: increased utilization of diesel engines (vs. gasoline engines); optimized cooling systems (including variable speed fan drives); radial tires (or wide base singles) and engine power and speed derating. Greater fleet-wide improvements could

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be realized by 1980 if production of diesel engines and radial (or wide base single) tires could be expanded more rapidly than present trends indicate.

No environmental or safety degradation could be identified with the suggested technology options. Noise would be reduced by the cooling system and tire changes but somewhat increased by the expanded diesel engine use. Exhaust emissions are substantially reduced by the substitution of diesel engines, and are not expected to increase as a result of other options. On the other hand, industry has expressed concern over the detrimental effects on fuel economy of existing and proposed safety, emission and noise regulations. There is uncertainty as to future air emission standards to be applied to trucks and buses. Therefore estimates of their impact on fuel consumption of 1980 vehicles were not attempted. There is no fuel economy penalty associated with current EPA or California standards using best technology.

The major technological shortcoming identified during the study lies in the realm of viable and equitable fuel economy measurement techniques. At the present time no accepted set of driving modes for either road tests or dynamometer tests exist by which fuel economy claims can be adequately judged. Furthermore, no scheme is evident by which a determination can be made for any particular vehicle as to the appropriate operational mode by which it should be evaluated. High priority needs to be given to the development of fuel economy test procedures. Since the real efficiency of the commercial vehicle fleet is determined by the fuel consumed relative to the work performed (the transportation of material and people), the final measure of commercial vehicle fuel economy should reflect productivity (such as ton miles or passenger miles per gallon of fuel consumed).

3. TECHNICAL DISCUSSION

3.1 SUBJECT VEHICLES, 1973 DATA BASE AND 1980 PROJECTIONS

For the purposes of this study, trucks and buses are defined solely on the basis of weight; that is trucks and buses considered herein are vehicles weighing in excess of 10,000 pounds. In practice, these vehicles are selected, purchased and operated to meet specific commercial needs and to make a profit. Therefore, strong market forces prompt adoption of cost saving technology. The primary consideration in the purchase of any commercial vehicle however is the ability to perform the specific mission. These missions vary so widely that a vast array of truck components (e.g., engines, transmission, axles, suspension, fans, seats, etc.) are marketed separately to facilitate purchaser selection and specification when ordering a new truck or fleet of new trucks.

The major truck builders offer a wide variety of options for each of their truck models. Options for lighter weight vehicles are predominately the manufacturers' own components. In the heavier vehicle categories, the manufacturer will likely fabricate only the frame and the cab; the engine, transmission, differential, and suspension, etc., are procured in accordance with the purchaser's specifications from component manufacturers. As a further complication, throughout the vehicle weight range, the vehicle manufacturer produces many vehicles which are not complete, and ready to use, but rather are power chassis to be delivered to an intermediate body manufacturer. Most school buses are fabricated in this manner and many van and dump bodies are added after delivery of the chassis to the final retailer. Normally truck tractors are delivered complete.

As a means of illustrating the options available to a purchaser, Table 3-1 lists the numerous truck chassis models and variations in wheel base, rated load, axle ratios, tire sizes, engine transmissions and auxilliary transmissions offered by one large truck manufacturer. To obtain the number of possible combinations

TABLE 3-1 VARIATIONS AVAILABLE FOR EACH COMPONENT

CHASSIS	WB	MAX. GVWR	MAX. GROSS LOAD	AXLE RATIO	TIRE SIZE	ENGINE	TRANS.	AUX. TRANS.
10,001 GVW & Above								
1510	2	2		9	2	5	3	
1600	8	4	4	16	4	1	5	
1600 (4x4)	4	2		1	2	1	5	
1700	9	4	4	14	3	2	5	
1700 (4x4)	4	2		2	2	2	5	
1750	9	4	1	14	3	1	5	
1800	9	4	2	14	3	3	8	
1850	9	5	2	10	2	2	10	
F-1800	4	4	2	9	3	3	7	5
F-1850	4	4		6	5	3	7	5
CO-1610A	9	4	3	14	3	1	5	
CO-1710A	9	4		14	3	2	8	
CO-1750A	9	4	3	14	2	1	4	
CO-1810A	9	4	3	14	3	2	6	
CO-1850A	9	4	3	14	2	2	4	
COF-1810A	9	4	3	18	3	2	5	
CO-1910A	8	4	1	16	2	6	10	
CO-1950A	8	4	1	14	2	3	10	
COF-1910A	8	4	2	18	2	6	10	
COF-1950A	8	4	2	18	2	3	10	
1910A	5	4	2	20	5	4	11	
2010A	5	4	2	20	5	5	12	2
2050A	5	4		20	5	4	15	3
2110A	5	4	2	20	4	4	17	3
F-1910A	5	4	2	33	5	4	12	4
F-2010A	5	4	1	33	7	7	18	7
F-2050A	5	4		14	7	2	16	7
2000 D	3	4	1	22	4	5	11	
F-2000 D	5	4	1	27	4	5	15	3
2070A	4	4	1	16	4	8	6	
F-2070A	7	4	1	26	6	8	7	2
4270	3	3	1	18	4	6	14	
4370	3	3	1	18	4	14	14	
1-4370	6	4	3	33	4	14	15	3
CO-4070A	5	3	1	14	4	17	8	
COF-4070A	4	4	1	27	4	17	9	
5050 (4x4)	3	2		6	5	3	6	
5070 (4x4)	3	2		6	5	17	4	
F-5050 (6x4)	6	4		26	4	3	7	5
F-5050 (6x6)	4	3		11	4	3	5	
F-5070 (6x4)	6	4		23	4	18	15	2

in any one model, one would multiply all the numbers on the line corresponding to the model. The total manufacturers' optional offering is the sum of all such products (note bodies are not listed).

Many of the manufacturers options, plus the body options, directly influence fuel economy but under the present system such variables are strictly in the hands of the purchaser. Furthermore, with so many options, very few trucks are ordered and built to a single specification. Thus, there is no 'representative' truck for purposes of fuel economy evaluation and thus the vehicle manufacturer is hard put to precisely predict the performance of his 'vehicles' unless a particular specification and a particular mission are prescribed.

To assist in the categorization of trucks, the industry has adopted eight (8) standard classes of trucks by weight. Weight classes 3 through 8 encompass the heavier vehicles (above 10,000 lbs. gross vehicle weight rating) and these are the vehicles considered in this report.

Data on the number of trucks registered in 1973 and the fuel consumed in the first years' operations has been accumulated and displayed in tables 3-2, 3, 4, 5 for the purpose of determining what vehicles, if improved, would have the greatest impact on national fuel conservation. These tables display for each weight class additional information about the reference trucks and buses such as:

Vehicle Description

- Gross vehicle weight; minimum and maximum limits
- Most popular models in use
- Principal uses such as pick-up and delivery
- Principal type of fuel used by new vehicles and the entire fleet

Fuel Consumption

- Gallons of fuel consumed by new 1973 calendar year trucks
- Total fleet fuel consumption
- Percent of fuel consumed based on all automotive consumption
- Average fuel economy (MPG) for each duty cycle
- Type of fuel used, gasoline or diesel
- Vehicle ton-miles/gallon or passenger-miles/gallon

Driving Mode has been divided into three categories:

- Local

  As typified by urban stop and go driving somewhat similar to the federal test procedure for emission certification testing of automobiles.

- Short Trip

  Under 200 mile round trip from base returning at night with a mixture of urban, suburban and highway driving between cities

- Long Trip

  One way - line haul high speed freight delivery or passenger carrying

Percent of the total vehicles by number for each of the three modes is shown.

Miles Traveled by weight class and driving mode:

- First year miles per year for new trucks
- Average miles per year traveled by specific driving mode and weighted average

These data were derived from information supplied by a number of sources shown immediately following the applicable tables.

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TABLE 3-2 MEDIUM DUTY TRUCK FUEL CONSUMPTION

Industry - Duty Class	Medium Duty		
Category - Weight Class	III	IV	V
Gross Vehicle Weight (Pounds)	10,001-14,000	14,001-16,000	16,001-19,500
Most Popular Model			

Principal Use	PICK-UP AND DELIVERY - AGRICULTURE - MOTOR HOMES		
Principal Type of Fuel Currently Being Used	Gas	Gas	Gas
New Truck Registrations 1973 Calendar Year* (1)			
By Weight Class	47,607	2,216	18,185
By Duty Class		68,008	
Total Medium Duty Trucks (2)			
By Weight Class	227,000	224,000	1,144,000
By Duty Class		1,595,000	
Gallons of Fuel Consumed by New 1973 Calendar Year Trucks (3) (Million Gals/Year)			
By Weight Class	84	5	59
By Duty Class		147	
Gallons of Fuel Consumed By Total In-Service Fleet (Million of Gals/Year) (4)			
By Weight Class	316	360	2,697
By Duty Class		3,373	
% of Fuel Consumed/Based on Total Fuel Used by All Automotive Sources) (5)			
By Weight Class	.2%	.2%	2.0%
By Duty Class		.2%	
Truck Miles Traveled Per Year (Miles/Year) For New Trucks By Weight Class (6)	10,000	12,000	15,000
% of (6) Trucks For Each Duty Class Be Utilized For (7)			
Local-Urban		65%	
Short Range		2%	
Long Range		33	
Average Miles Per Year Traveled For Each (8) Class Of Operation Driving Mode (9)			
Local-Urban***		8,900	
Short Range		20,800	
Long Range		46,000	
Weighted Average		10,400	
Average Truck Fuel Economy For Each Weight Class By Specific Driving Mode (MPG)	Gas	Gas	Gas
Local-Urban (9)	6.0	6.0	6.0
Short Range	6.0	7.2	6.2
Long Range	6.0	7.2	6.2
Weighted Average	6.0	7.0	6.2
Vehicle Ton Miles Per Gal. For Each Duty Class By Specific Driving Mode (Ton-Miles/Gal.) (10)			
Local-Urban	16.0	16.0	17.4
Short Range	17.4	18.0	18.4
Long Range	17.4	18.0	18.4
Weighted Average	17.0	18.1	18.0

* Calendar Year from 1/1/73 to 12/31/73

*** Local-Urban - Pickup and Delivery Service within the City
Short Range - Under 200 Mile Round Trip-Returning to Base Each Night
Long Range - Over 200 Mile - in Line Hauling Across Country

TABLE 3-3 LIGHT HEAVY DUTY TRUCK FUEL CONSUMPTION

Industry - Duty Class		Light Heavy Duty	
Category - Weight Class		VI	
Gross Vehicle Weight (Pounds)		19,501 - 26,000	
Most Popular Model			
		VAN	DUMP STAKE
Principal Use		WHOLESALE & RETAIL - BEVERAGE DELIVERY - DUMP TRUCK - AGRICULTURE	
Principal Type of Fuel Currently Being Used	Gas		Diesel
New Truck Registrations 1973 Calendar Year* (1)			
By Weight Class	233,369		4,270
By Duty Class		237,639	
Total Light Heavy Duty Trucks (2)			
By Weight Class	2,070,000		73,000
By Duty Class		2,143,000	
Gallons of Fuel Consumed by New 1973 Calendar Year Trucks (3) (Million Gals/Year)			
By Weight Class	7.0		27
By Duty Class		34	
Gallons of Fuel Consumed By Total In-Service Fleet (Million of Gals/Year) (4)			
By Weight Class	3,440		98
By Duty Class		3,538	
% of Fuel Consumed/Based on Total Fuel Used by all Automotive Sources) (5)			
By Weight Class	0.17		0.17
By Duty Class		0.347	
Truck Miles Traveled Per Year (Miles/Year) For New Trucks By Weight Class (6)	11,000		27,000
% of Total Trucks For Each Duty Class By Primary Use (6)			
Local-Urban	69%		1%
Short Range	7%		52%
Long Range	24%		47%
Average Miles Per Year Traveled For Each Duty Class By Specific Driving Mode (6)			
Local-Urban***	5,700		15,400
Short Range	20,400		28,400
Long Range	24,600		53,000
Weighted Average	19,500		20,000
Average Truck Fuel Economy For Each Weight Class By Specific Driving Mode (MPG) (7)	Gas		Diesel
Local-Urban	5.1		6.5
Short Range	5.7		7.5
Long Range	6.0		7.8
Weighted Average	5.8		6.8
Vehicle Ton Miles Per Year for Each Duty Class By Specific Driving Mode (Ton-Miles/Gal.) (8)			
Local-Urban	28.2		51.5
Short Range	56.4		66.5
Long Range	71.1		66.5
Weighted Average	57.0		66.2

* Calendar Year from 1/1/73 to 12/31/73

*** Local-Urban - Pickup and Delivery Service within the City
Short Range - Under 200 Mile Round Trip-Returning to Base Each Night
Long Range - Over 200 Mile - In Line Hauling Across Country

TABLE 3-4 HEAVY DUTY TRUCK FUEL CONSUMPTION

Industry - Duty Class	Heavy Duty			
Category - Weight Class	VII		VIII	
Gross Vehicle Weight (Pounds)	26,000-33,000		Over 33,000	
Most Popular Model	DUMP	VAN		
Principal Use	DUMP TRUCK - READY MIX CONCRETE - GARBAGE - FUEL DELIVERY			
Principal Type of Fuel Currently Being Used	Gas	Diesel	Gas	Diesel
New Truck Registrations (1973 Calendar Year* (1)(2))				
By Weight Class	27,000	14,000	15,000	127,000
By Duty Class	41,000		142,000	
Total Heavy Duty Trucks (3)				
By Weight Class	324,000	100,000	434,000	700,000
By Duty Class	424,000		1,134,000	
Gallons of Fuel Consumed by New 1973 Calendar Year Trucks (3) (Million Gals/Year) (3)				
By Weight Class	337	324	742	2,000
By Duty Class	661		2,742	
Gallons of Fuel Consumed By Total In-Service Fleet (Million of Gals/Year) (3)				
By Weight Class	773	897	2,044	8,457
By Duty Class	1,670		10,501	
% of Fuel Consumed/Based on Total Fuel Used by all Automotive Sources) (3)				
By Weight Class	1%	.7%	3.2%	6.0%
By Duty Class	2.4%		10.1%	
Truck Miles Traveled Per Year (Miles/Year) For New Trucks By Weight Class (3a)	37,000	33,000	40,000	67,000
% of Total Trucks For Each Duty Class As Follows (3a)	Gas		Diesel	
Local-Urban	26%		55%	
Short Range	20%		13%	
Long Range	54		32%	
Average Miles/Per Year Traveled for Each Duty Class By Specific Driving Mode (4)	Gas		Diesel	
Local-Urban***	22,700		22,600	
Short Range	36,800		44,000	
Long Range	80,600		99,000	
Weighted Average	39,000		64,000	
Average Truck Fuel Economy For Each Weight Class By Specific Driving Mode (MPG) (5)	Gas	Diesel	Gas	Diesel
Local-Urban	5.1	6.0	4.9	5.7
Short Range	5.3	6.0	4.9	5.7
Long Range	5.3	6.0	4.9	5.7
Weighted Average	5.3	6.0	4.9	5.7
Vehicle Ton Miles Per Year for Each Duty Class By Specific Driving Mode (Ton-Miles/Gal.) (6)				
Average	58.7	66	73.5	85.5

* Calendar Year from 1/1/73 to 12/31/73

*** Local-Urban - Pickup and Delivery (Service within the city)
Short Range - Under 200 Mile Round Trip-Returning to Base Each Night
Long Range - Over 200 Mile - in Line Hauling Across Country

SOURCES OF DATA TABLES(3-2,3-3,3-4)

Category III-V (Medium Duty)

(1) 1973 Registration	Wards Automotive Yearbook 1974
(2) Total in Service	American Trucking Association (ATA) Data for 1972 updated to 1973 by a factor of 1.025 plus 1973 motor truck facts, Motor Vehicle Manufacturers Association (MVMA)
(3) Fuel Consumed 1973 Model	Estimate based upon average mileage per year and fuel consumption data of typical vehicles. Road user and property taxes on selected vehicles 1973 U.S. Dept. of Trans, ATA data.
(4) Fuel Consumed, All Years	ATA data for 1972 updated to 1973 by a factor of 1.025, road user and property taxes on selected vehicles 1973, U.S. Dept. of Trans. and ADL estimates
(5) % of Total Fuel for All Automotive Sources	Estimate based upon 1972 ATA data, and 1972 highway Statistics (DOT)
(6) Mileage per Vehicle per Year	ATA data, 1972
Average Fuel Consumed per Vehicle, Miles/Gallon	" " "
Ton Miles per Gallon	ATA data, 1972

Category VI-VIII (Light Heavy Duty and Heavy Duty)

(1) (2) (3) (4) (5) (6)	References same as above except for 1973 production and registration.
(7) 1973 Registration	Estimate based upon Wards Automotive Year book 1974, and 1973 Motor Truck Facts.

TABLE 3-5 BUS FUEL CONSUMPTION

Industry - Duty Class

Category - Weight Class

Gross Vehicle Weight (Pounds)	SCHOOL	INTERCITY	TRANSIT
Most Popular Model			
Principal Type of Fuel Currently Being Used	Gas*	Diesel	Diesel
New Bus Registrations 1973 Calendar Year*(1)	44,488	4,184	3,200
Total Buses (1)	323,000	30,367	48,286
Gallons of Fuel Consumed by New 1973 Calendar Year Buses (Million Gals/Year (2)	4	26	31
Gallons of Fuel Consumed By Total In-Service Fleet (Million of Gals/Year) (2)	253	202	293
% of Fuel Consumed Based on Total Fuel Used By All Automotive Sources) (2)	.2	.22	.14
Bus Miles Traveled Per Year (Miles/Year) For New Buses By Weight Class (2)	7,500	52,700	43,000
Average Miles Per Year Traveled (2)	7,500	52,700	28,500
Average Bus Fuel Economy For Each Class (MPG) (3)	7.4	6.0	[illegible]
Passenger Miles Per Year for Each Class (Thousands of Passenger-Miles/Year) (3)	[illegible]	19	[illegible]

* Calendar Year from 1/1/73 to 12/31/73

SOURCES OF DATA TABLE(3-5)

(1) 1973 Registration	Estimate based on Wards Automotive Yearbook, 1974; 1973 Motor Truck Facts, and letter from GMC, F.W. Krey, to U.S.E.P.A., Dr. William Roper, giving details of bus population and uses. National Association of Motor Bus Owners Yearbook for 1973, submission by Stanley Hamilton, Director of Public Affairs National Association of Motor Bus Owners (NAMBO). Transit Fact Book 73-74 American Transit Association.
(2) Fuel Consumed, 1973 Model Year	Data from 1972 Highway Statistics projected to 1973, NAMBO and ADL estimates.
Fuel Consumed by In Service Fleet	
% of Total Fuel for All Automotive Sources	
Average Mileage per Vehicle per Year	
Average Fuel Consumed per Vehicle, Miles/Gallon	
(3) Passenger Miles per Gallon	Estimate based upon 1972 Highway Statistics and manufacturers data.

3.1.1 New Truck Registration Versus Driving Mode

In an attempt to select reference vehicles, an analysis was made of new truck registrations and how these new trucks are used in either local, short haul, or long haul duty. Figure 3-1 displays this information and shows that:

- The largest quantity of new 1973 vehicle registrations occurred in Class VI, including school buses, and these vehicles are principally used for local start and stop duty. These vehicles are nominally gasoline powered.
- The second largest new vehicle registration is in Class VIII local duty. Transit buses have been included in this subset of Class VIII. These vehicles are nominally diesel powered.
- Class III, IV, and V trucks used for local service represent the third largest registry of new vehicles. They are essentially all gasoline powered. There has been a large increase in Class III in the last 2-3 years.

3.1.2 New Truck Fuel Consumption Versus Driving Mode

A similar analysis was conducted to estimate fuel consumption by new trucks for each weight class and each driving mode. The results are shown in Figure 3-2.

- Class VIII vehicles account for the largest use of fuel. The driving mode fuel consumption closely follows the pattern set by the number of new vehicle registrations as shown in Figure 3-1.
- Class VI trucks and school buses used for local service represent the second largest fuel consumption subset. (Note the daily transportation of some 18 million school children is included in these figures.)

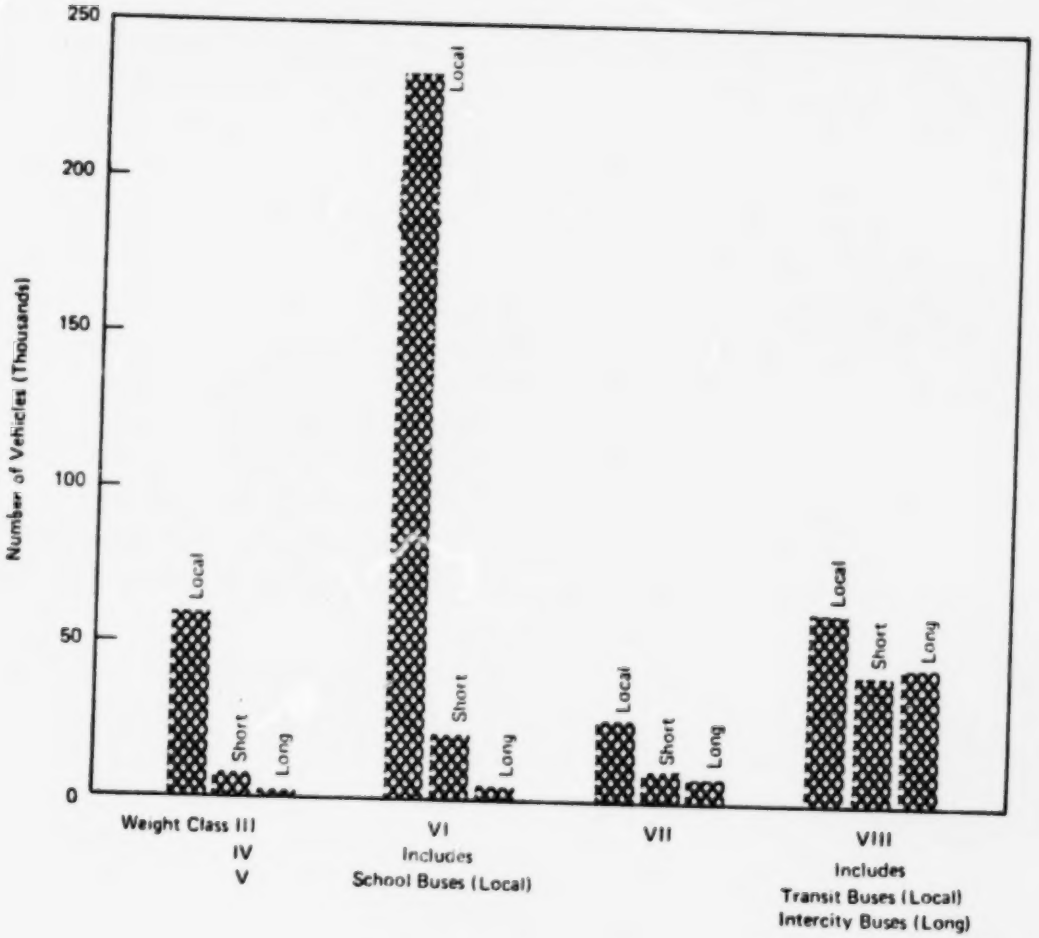

Figure 3-1 New Truck and Bus Registrations, 1973 Calendar Year, By Weight Class and Driving Mode

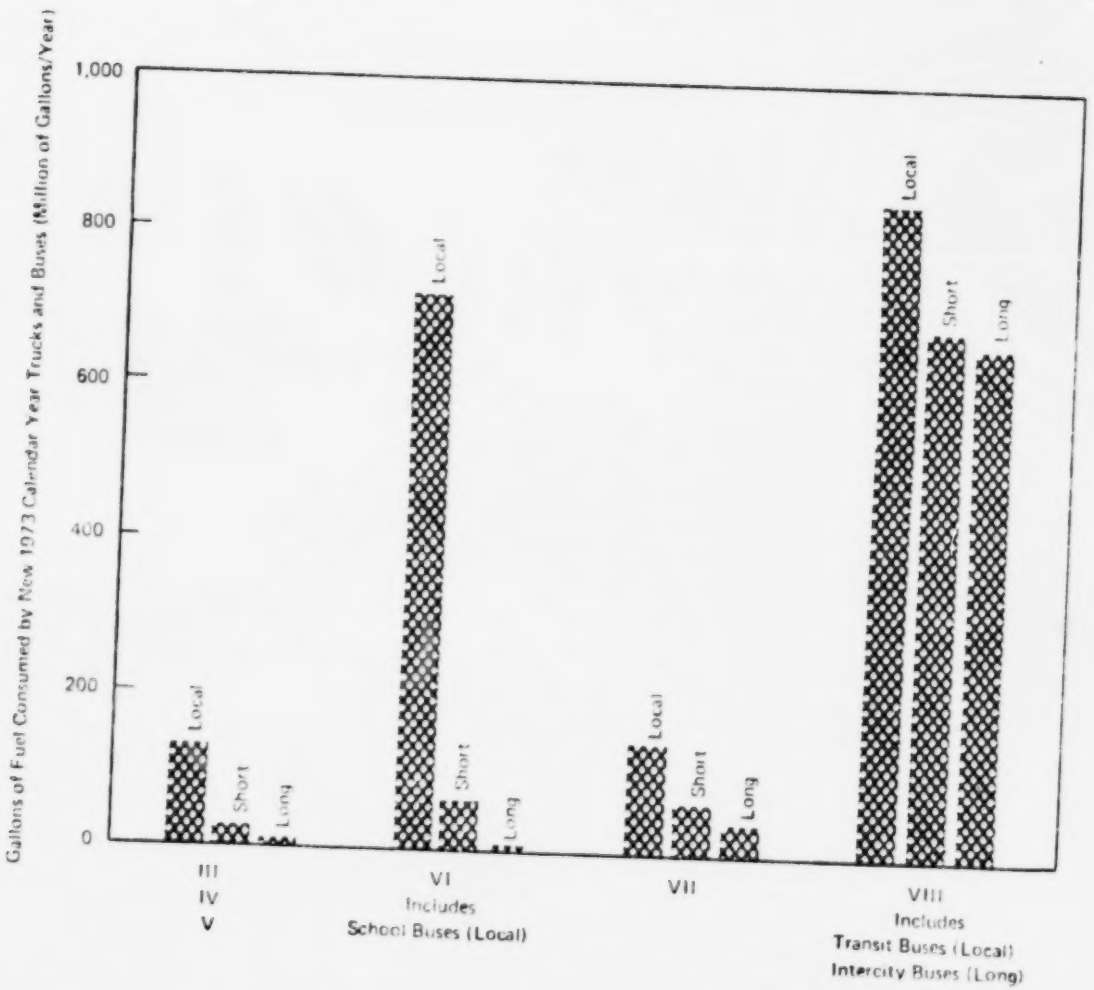

Figure 3-2 Truck and Bus Fuel Consumption by Weight Class and Driving Mode for New 1973 Calendar Year

3.1.3 Selection of Reference Vehicles

Based on the results of the fuel consumption estimates it was concluded that the four reference vehicles which could most impact total fuel consumption are:

- Class VIII local service diesel powered vehicles including cement mixers, dump trucks, delivery tractor-trailers, and transit buses.
- Class VI local service gasoline engine powered school buses, delivery vans and dump trucks.
- Class VIII diesel powered vehicles including large vans, tractor trailers, tank trucks and truck trailers used in short haul and long haul service respectively.

No other subset of weight class/driving mode accounts for as much as 25% of Class VI and VIII. Thus, while there are more medium duty vehicles (Classes III, IV & V) being registered in the local use category than Class VIII short or long haul subsets, the lower utilization of the medium duty vehicles reduces the fuel consumption of these vehicles to minor proportions.

3.1.4 Projections of 1980 New Truck and Bus Registrations

To complete the necessary data for evaluating potential improvements a forecast was made of 1980 new truck and bus registrations. For comparison purposes, Table 3-6 provides a recapitulation of information showing the present new truck registrations by weight class, driving mode, and type of engine. Table 3-7 provides estimates of new 1980 truck and bus registrations, also by weight, driving mode, and engine types.

Comparison of these tables shows the estimated increase in total number of new truck and bus registrations and the estimated increase in the proportion of diesel as compared to gasoline engine powered vehicles. The percent of diesel powered vehicles in Class VII will increase from 34% to 77% and in class VI from 2% to 28%. This increase in diesel engine powered vehicles will require a major effort in application and production capacity expansion. The

TABLE 3-6 1973 NEW TRUCK & BUS REGISTRATIONS BY WEIGHT CLASS, DUTY MODE & POWER PLANT

All Trucks & Buses

Mode	Weight Class	III IV, V	VI	VII	VIII	School	Tran.	I. City	Total
	Local	59,847	191,101	25,420	55,850	44,488	3,200	--	379,906
	Short	6,121	22,339	10,020	44,910	--	--	--	83,390
	Long	2,040	4,399	5,560	41,240	--	--	4,184	57,423
	TOTAL	68,008	217,839	41,000	142,000	44,488	3,200	4,184	525,679

Diesel Powered Only

Mode									
	Local	--	3,160	4,900	44,450	--	3,200	--	55,710
	Short	--	932	4,620	41,910	--	--	--	47,512
	Long	--	128	4,480	40,640	--	--	4,184	49,432
	TOTAL	--	4,270	14,000	127,000	--	3,200	4,184	152,654

Gasoline Powered Only

Mode									
	Local	59,847	187,941	20,520	11,400	44,488	--	--	324,196
	Short	6,121	21,357	5,400	3,000	--	--	--	35,878
	Long	2,040	4,271	1,080	600	--	--	--	7,991
	TOTAL	68,008	213,569	27,000	15,000	44,488	--	--	368,065

TABLE 3-7 PROJECTIONS FOR 1980 - NEW TRUCK AND BUS REGISTRATION BY WEIGHT CLASS, DUTY MODE AND POWER PLANT

All Trucks & Buses

Mode	Weight Class	III IV, V	VI	VII	VIII	School	Tran.	I. City	Total
	Local	59,800	220,000	26,700	85,800	44,000	5,000	--	441,300
	Short	6,100	25,000	10,300	70,400	--	--	--	111,800
	Long	1,100	5,000	6,000	63,800	--	--	6,000	81,900
	TOTAL	67,000	250,000	43,000	220,000	44,000	5,000	6,000	635,000

Diesel Powered Only

Mode									
	Local	--	52,000	16,700	82,800	--	5,000	--	156,500
	Short	--	25,000	10,300	70,400	--	--	--	105,700
	Long	--	5,000	6,000	63,800	--	--	6,000	80,800
	TOTAL	--	82,000	33,000	217,000	--	5,000	6,000	343,000

Gasoline Powered Only

Mode									
	Local	59,800	168,000	10,000	3,000	44,000	--	--	284,800
	Short	6,100	--	--	--	--	--	--	6,100
	Long	1,100	--	--	--	--	--	--	1,100
	TOTAL	67,000	168,000	10,000	3,000	44,000	--	--	292,000

industry has indicated diesel engine production commitments which support these production levels.

3.2 FUEL ECONOMY MEASUREMENT

The following section discusses some general and specific problems and methods of measuring fuel economy on completed heavy-duty vehicles.

3.2.1 Elements of a Fuel Economy Measurement Technique

There are three main elements to a complete vehicle fuel economy measurement system.

1. A representative operating sequence;
2. An accurate instrumentation method; and
3. A suitable test environment.

These elements are discussed at length in the section on Fuel Economy Test Procedures dealing with passenger cars. Accurate, repeatable, and comparable measurements are necessary in any measurement system. Passenger car measurements are presently obtained by using a chassis dynamometer to simulate on-the-road power requirements while measuring the quantity of fuel consumed by mass, volume, or carbon balance techniques. Ambient test conditions must be controlled to reasonable tolerances. Representative urban and highway operating schedules are required to properly program the dynamometer and/or vehicle control functions.

Two major problems become apparent when attempting to apply passenger car measurement techniques to commercial vehicles. The first is the fact that there have been no representative or generally accepted operating schedules (driving cycles) developed for trucks and buses. The second is that trucks are built in such a wide variety of sizes, shapes, and configurations, and have such varied applications that arriving at a 'typical' or 'average' truck configuration is not meaningful.

The various major truck manufacturers have selected road courses or proving ground schedules, but most are based on local convenience or judgmental factors rather than any representative data base of overall truck and bus usage patterns. EPA emission tests for heavy duty vehicles are in fact engine-dynamometer tests only. The present engine test schedules have been developed by industry consensus but the bases are not well documented. These tests, in any event only treat engine related efficiencies. EPA has under development a representative urban air quality related driving cycle which will be expressed in terms of engine operating parameters and applied to engine dynamometer tests. The results of this research could provide an interim fuel economy test schedule for urban usage (representing 38% of total truck vehicle miles traveled). It will be necessary to similarly characterize the remaining 62% of vehicle miles traveled, by developing an interim over-the-road (and perhaps suburban) driving schedule to complement the urban schedule and thereby treat all aspects of truck and bus usage.

The various classes of trucks and buses are described in section 3.1 as well as the problems encountered in characterizing them. The wide range of weight classes, driving modes and vehicle characteristics significantly complicates the problem of comparative fuel economy measurement.

The delineation of these problems is not to suggest that there is no way to arrive at reasonable fuel economy measurement procedures for trucks and buses, but rather to point out that in the short term there are some rather formidable obstacles to overcome. These obstacles have forced the authors to make significant assumptions to facilitate intercomparison of available data. The section of the report to follow examines current measurement methods and their limitations in more detail.

3.2.2 Existing Practices for Fuel Economy Measurement

Present practices for heavy duty vehicle fuel economy measurement include: 1) engine dynamometer mapping of brake specific

fuel consumption (BSFC)*; 2) fleet operational data monitoring; 3) component evaluation, and; 4) computer aided simulation modeling.

Each engine manufacturer, in the course of developmental work, 'maps' an engine's fuel consumption at various speeds and loads. This mapping provides a basis for judging the performance of one engine model relative to another and also for evaluating the impact of design and hardware changes. To assess the fuel economy of one engine relative to another in actual application requires knowledge of the operating speeds and loads during road usage. For example, if engine A consumes 10% less fuel than engine B at full load and has equivalent fuel consumption at all other speeds and loads one might conclude that A is more efficient than B. However, if when installed in a truck and operated over a road course, full load operation is never encountered, then the actual fuel economy of the two engines will be the same for that particular duty cycle.

EPA is currently employing two engine dynamometer test sequences, one for gasoline engines having nine modes of operation at a constant engine speed and one for diesel engines having 13 modes at two different engine speeds. The various modes are selected to cover the ranges of expected loading at representative engine speeds. The modes are weighted according to the expected frequency of operation to arrive at a composite emission rate. Fuel flow rate measurements are taken at each mode and are used for engine emission certification. At the present time these engine test schedules represent the only commonly used procedures for engine cycle testing. An expedient, weighted average fuel consumption value can be derived from such tests and used as a limited comparative tool. The major weaknesses in applying current EPA emission test procedures as fuel economy tests include: 1) representative vehicle miles traveled can not be determined since only the engine is involved; 2) the gasoline 9-mode test does not

*BSFC is lbs. of fuel consumed per brake horsepower-hour

incorporate a full load test point, a characteristic operating mode for heavy duty trucks; 3) the mode weighting factors may not be representative of overall truck and bus usage.

The weaknesses of the present EPA procedures do not preclude quantitative comparison of engines for fuel economy purposes. They are related here simply as cautions against attempts to derive precise predictions of fuel economy for a given vehicle based upon engine dynamometer test data.

Much of the heavy duty trucking industry and most transit and intercity buses are part of relatively large fleets of vehicles. The management of such fleets often includes close monitoring of maintenance and operating costs. Since fuel is an easily identifiable operating expense, fuel economy is often monitored. The measurement procedure is simply a recording of all fuel added and incremental miles traveled. Such data are ideal from the standpoint of monitoring actual truck usage under varying environmental conditions. However, large quantities of data taken over extended time periods are necessary to make reasonable decisions on relative improvements brought about through use of alternate technologies. One must assume that the variations in fuel economy introduced by such things as random assignments of trips, loads, and drivers are averaged out of long term data and that such data are statistically significant. Monitoring several carefully selected fleets in various geographic regions could provide an accurate data base for calculating total fuel usage by the U.S. commercial fleet. Fleet measurement as a technology evaluation scheme has been used in this report but its use as an enforcement tool for a regulatory process would not be feasible.

Individual component efficiency evaluation is a common means of determining the benefit of a proposed hardware modification. To understand the relationship of a single component to total vehicle fuel economy one needs to examine where the energy is dispersed in a moving vehicle. The energy available from the fuel is expended in the engine and accessories because of thermal and operating losses; in the driveline from parasitic losses (friction);

in the tires from rolling resistance; in the body from contact with moving air (aerodynamic drag); and in the brakes (kinetic energy reduction). The energy input to a given component is usually measurable. For example, the power required to turn an air conditioning compressor at a given speed can be measured. Then for a given vehicle operating condition a change in power resulting from elimination or change in the compressor can be determined and the net savings can be related back to engine net horsepower output. The expected fuel economy benefit is then derived from the engine fuel 'map' previously described. Equation (1) is a simplified mathematical expression of the contributing elements of fuel consumption.

$$\text{ENERGY} = \begin{array}{l}\text{ENGINE LOSS + ACCESSORY LOSS +} \\ \text{DRIVELINE LOSS + TIRE LOSS +} \\ \text{AERODYNAMIC LOSS + BRAKING LOSS} \\ \text{+ STORED ENERGY}\end{array} \qquad (1)$$

Stored energy would be zero for an out and back mission where the vehicle starts and ends at the starting point.

Field testing of components is usually performed to verify experimental analysis. Two major problems arise when attempting to determine vehicle fuel economy improvements from component analysis: 1) the difficulty in duplicating on-the-road operational modes with laboratory apparatus; and 2) the fact that when considering a number of changes at one time there are often interactions between components that confound the analysis.

An interaction exists, for example, when component A employed alone results in a 10% improvement, likewise component B saves 10%, but when combined in an application only 15% improvement results. Because of the great variety of components found on trucks and their diverse usage patterns, it is difficult to predict the aggregate fuel economy of vehicles because of such interactions. If some consensus driving cycle existed to define representative operating environments such as those examined in the Census of Transportation[1] namely; local, short, and long haul,

it would be possible to predict some maximum obtainable fuel economy performance for a given truck knowing the theoretical characteristics of the power consuming elements. However, lacking specific driving cycles, some other approach to evaluating vehicle fuel economy benefits derivable through incorporation of numerous technology options is needed.

An approach to analyzing many aspects of on-the-road truck performance, including fuel consumption, is computer aided simulation. Several vehicle and engine manufacturers have developed mathematical models which characterize a vehicle and its operating environment down to the level of individual component performance. The performance of major components affecting energy loss are characterized by empirically derived relationships. The road network of interest is characterized in terms of stops along the route, road conditions, and speed limits. By applying several assumptions primarily related to driving techniques, a truck which has never been built can have its performance and operating economies over a specific road route estimated. The Cummins Engine Company[2] has one of the most sophisticated models yet developed. It accounts for many real life environmental factors including wind effects and altitude. Some of the components characterized in the simulation program are: engines; transmissions; axles; tires; bodies; significant accessories; and cargo.

Output of the program includes trip time, trip length, percent of time at various speeds and loads and total fuel consumed. Comparisons of such computer simulations with actual truck performance have been made and are accurate within $\pm$10%. Simulation programs have as their main advantages, 1) the ability to predict performance of complete vehicles over any road route without operating the vehicle; and 2) the ability to take into account the interactive effects of many technology options in a single analysis. The weaknesses of vehicle simulation modeling include assumptions which gloss over the large effects of driver variability, climatic variability and traffic variability. While route characterization has been limited to primarily long haul routes to date, it is possible to add urban and suburban routes.

Use of a mathematical model as a regulatory approach to fuel economy measurement would be impractical because it would be likely challenged as synthetic and arbitrary even if the relationship to road performance were well established. In addition, because of the mathematical characterization of component performance, the regulations might provide greater motivation to effect "paper" improvements.

Extensive vehicle utilization data synthesized through computer modeling techniques appears to be the most promising approach to generating representative driving cycles for truck and bus usage.

3.2.3 Areas of Future Development

The development of 'representative' driving cycles for various classes of trucks and buses is an active program within the Environmental Protection Agency. Data are being gathered from vehicle operating environments in New York and Los Angeles. A variety of trucks and buses are being monitored during the course of their daily work routines. An engine testing sequence is expected to result. There will also be a link to air quality in that data on miles traveled and corresponding engine usage will be available. Chassis dynamometer or road route driving cycles can also be generated from this data base. However, all data are being collected in the urban environment and therefore will not be applicable to long haul, over-the-road, operation. Some form of fuel consumption measurement will be made although a specific technique has not been determined. It is doubtful that the revised urban air quality related emission test will be in effect before 1980. A program for development of a representative engine fuel economy test cycle is soon to be initiated under EPA auspices.

Industry and government efforts at improving the comprehensiveness and accuracy of simulation modeling will likely accelerate in the next few years. The characterization of major U.S. road networks including both urban and over-the-road segments is a likely step. A reduction in number of assumptions by the

substitution of experimentally supported relationships for maneuvers (such as turning corners and random traffic congestion constraints) would improve prediction accuracy. A series of representative short haul and long haul driving cycles could probably be developed by simulation techniques in the 1980 time frame.

3.2.4 Appropriate Measurement Units

a. Consideration of Fuels: Diesel and Gasoline

The heat content of diesel fuel on a volume basis is approximately 10% higher than gasoline. Therefore, if these two types of automotive fuels were priced solely on their heat content, diesel fuel should be 10% higher than gasoline and diesel powered vehicles to be fuel cost comparable should show a 10% improvement over similar gasoline powered vehicles. A look at the current marketplace shows that even with its higher heat content, diesel fuel is generally equal to or slightly cheaper than the regular grades of gasoline. This pricing difference is generally explained by calling the diesel fuel fraction a byproduct of the current petroleum refining process; that process being geared to maximize the production of gasoline. We know of no study in the open literature that addresses costs in terms of various increased demands for diesel fuel at equivalent sacrifices for gasoline production. However, it is clear that for the current diesel fuel demand, less complex processing is required than for gasoline with attendant lower processing costs and product losses.

A program is currently being planned to model refinery operations so that cost tradeoffs and efficiencies can be more precisely defined. In the absence of these data and since the vehicles with which we are concerned are commercial in nature and the two fuel prices are nearly equivalent, we have arbitrally decided to consider diesel fuel and gasoline to be equivalent on a volume basis.

b. Vehicle Productivity

Commercial vehicles are selected, purchased and operated to transport goods or passengers from one point to another and thus generate a profit for the vehicle owner. In the search for improved fuel economy, the capacity to transport goods and passengers must not be restricted. The analyses of commercial vehicle fuel economy therefore must take into full account the growing demand for goods movement and likely increases in passenger movement and must examine the individual vehicles within the nationwide fleet on a productivity basis. Each vehicle has a design (or rated) cargo or passenger capacity which has been generally set by the mission the vehicle is to perform. The purchaser of the commercial vehicle seldom has the option to reduce vehicle size and weight (as do purchasers of passenger cars by going from standard to intermediate to compact or subcompact autos) without drastically impacting his capacity to perform the mission. A carryover of the simple mile per gallon fuel economy measure from the automobile would provide misleading indications that smaller trucks and buses would be more fuel economic. In fact if such smaller vehicles were forced into use by fuel economy regulations the movement of goods and people would be restricted and a higher aggregate fuel consumption would occur. This is clearly counter productive.

Management has the job of selling its full capacity to transport goods or people; unfortunately consumer demand for these services fluctuate and in the case of trucking operations bulk limitations may supersede weight restrictions resulting in less than capacity loading. However, many vehicles are operated at capacity and increasing cost pressures will force even better capacity utilization (perhaps at the expense of increased shipment delays). Therefore, fuel economy in the commercial vehicle area is more appropriatly characterized by combining productivity ratings with mile per gallon performance such as:

- Gross vehicle weight rating x miles per gallon;
- Gross combination weight rating x miles per gallon
- Cargo capacity x miles per gallon

- Passenger seats x miles per gallon; or
- Other productivity measures x miles per gallon

3.2.5 Regulatory Considerations

Accurate and repeatable methods for fuel measurement over a representative driving schedule using representative vehicles are essential elements to a regulatory comparative fuel economy improvement program. At the present time, neither the representative driving schedules nor representative vehicles can be determined which would provide reasonable assurance of achieving the fuel economy improvement objectives on an equitable regulatory basis.

Engine fuel mapping, in combination with component efficiency testing, computer aided simulation models, and truck fleet monitoring are all being used for manufacturer and purchaser decision-making with regards to individual vehicle fuel economy. That means the purchaser can reasonably estimate fuel consumption of a vehicle on his service route, but he cannot use these techniques to produce universal fuel consumption data for a manufacturer's annual production. Much data from fleet operations and further use of computer simulations will be required before rational decisions can be made regarding truly representative driving cycles and the means to unequivocally identify the cycle to be used as the test for any given vehicle.

Arbitrary test schedules can of course be determined on road courses or on dynamometers, but the development of truly useful procedures will take more time than is available for implementation of regulations by 1980. The one clear point is that commercial vehicle fuel economy should be measured and judged on the basis of work productivity.

3.3 IMPROVEMENT OPTIONS

The following sections are technical discussions and evaluations of the various improvement options considered. Following the technical discussion of each option (Section 3.3.1 - 3.3.5)

is a chart summarizing the fuel economy and accompanying production restraints. The three driving modes -- local, short and long -- are represented. The percentage of fuel economy improvement due to a particular option is discussed for each of the driving modes in the following sections. The percentage of 1973 vehicles already incorporating the particular option was determined from existing data and is included in the summary chart for each option.

The fleet fuel economy improvement percentage is obtained by determining the total number of vehicles of each driving class projected for 1980. The difference between the number of 1973 vehicles using the option and the projected number of 1980 vehicles, assuming all of these could use the option, would represent the increase in the number of vehicles using the option. This figure combined with the fuel economy improvement per vehicle yields the total increased fleet fuel economy possible by 1980 before production considerations.

The estimated production capacity is based on two considerations. The first factor to be considered is the anticipated vehicles of the type and class which can incorporate the particular option. For example, using fuel injection, this percentage is the projected ratio of gasoline engines to the total number of engines produced, both gasoline and diesel.

The second consideration is the estimated proportion of the production capacity which would be converted to produce vehicles incorporating the option by 1980. This estimation is based on the associated technology, the additional cost and the purchaser's acceptance. By multiplying the production capacity and the total fleet fuel economy improvement, the maximum attainable fuel economy improvement possible by 1980 is calculated.

3.3.1 Diesel Engines

3.3.1.1 Diesel Substituted for Gasoline Engines - The substitution of diesel engines for gasoline engines in medium and heavy duty

trucks can produce a substantial reduction in fuel consumption. This is due to the improved efficiency of the diesel engine as compared to a gasoline engine particularly under light load conditions. This improved efficiency results from a combination of differences between these engine. The diesel engine operates at higher pressures and temperatures than a gasoline engine; thus it exhibits higher thermal efficiency. Secondly, a diesel is controlled by limiting the fuel, while the air necessary for combustion is freely drawn into the cylinder. In gasoline engines the air and fuel are limited by the carburetor throttle plate setting. This means that during the intake stroke of a gasoline engine, the piston must draw in air through a quantity limiting restriction. This creates pressure losses above those of a diesel engine which subtract from the gasoline engine's useful work output. This situation is aggravated at light loads such as during engine idling or low speed urban driving.

The estimated fuel economy improvement for various truck weights in local, short, and long haul service are summarized in Table 3-8. The sources for the reported statistics are given in the right hand column. The improvements shown in Table 3-8 are based on the direct substitution of diesel engines for gasoline engines in identical vehicle operation under the type of service indicated. The ranges of reported improvements are indicated. In addition, the authors have indicated their estimated ranges of improvements taking into account various practical factors. For example the high percentage of improvement reported by International Harvester was considered overly optimistic and was therefore arbitrarily deleted from the authors summary estimates. Another source of comparison is a study of gasoline and diesel truck emissions and fuel economies over a standard urban road route conducted for EPA by Southwest Research Institute. These data, plotted in Figure 3-3, verify the substitution improvements already cited for the diesel and graphically illustrate the possibility of nearly doubling productivity in ton miles/gallon when using diesel engines in larger trucks.

TABLE 3-8 FUEL ECONOMY IMPROVEMENT ESTIMATES - DIESEL ENGINE SUBSTITUTION FOR GASOLINE ENGINE

Weight Class	Use Local	Short	Long	Source
	Percent Improvement in MPG			
III-VIII	60		45	I.H.
III-VIII	◄--- Up to 30-40 ---►			Ford
III-VIII	◄--- Up to 30-40 ---►			Schweitzer
III-VIII	20-40	10-20	5-20	ADL
III-VIII	20-40	10-20	5-40	Author's Estimate

Sources:

I.H. - International Harvester Bulletin No. 261 September 1972, Page 4

Ford - Response to 120 day study Public Docket, letter dated August 20, 1974 from D.A. Jensen

Schweitzer - Response to 1290 day study to Public Docket, letter dated August 14, 1974 from Carl R. Canfield

ADL - Arthur D. Little, Report to DOT/EPA "A Study of Technological Improvements in Automobile Fuel Consumption."

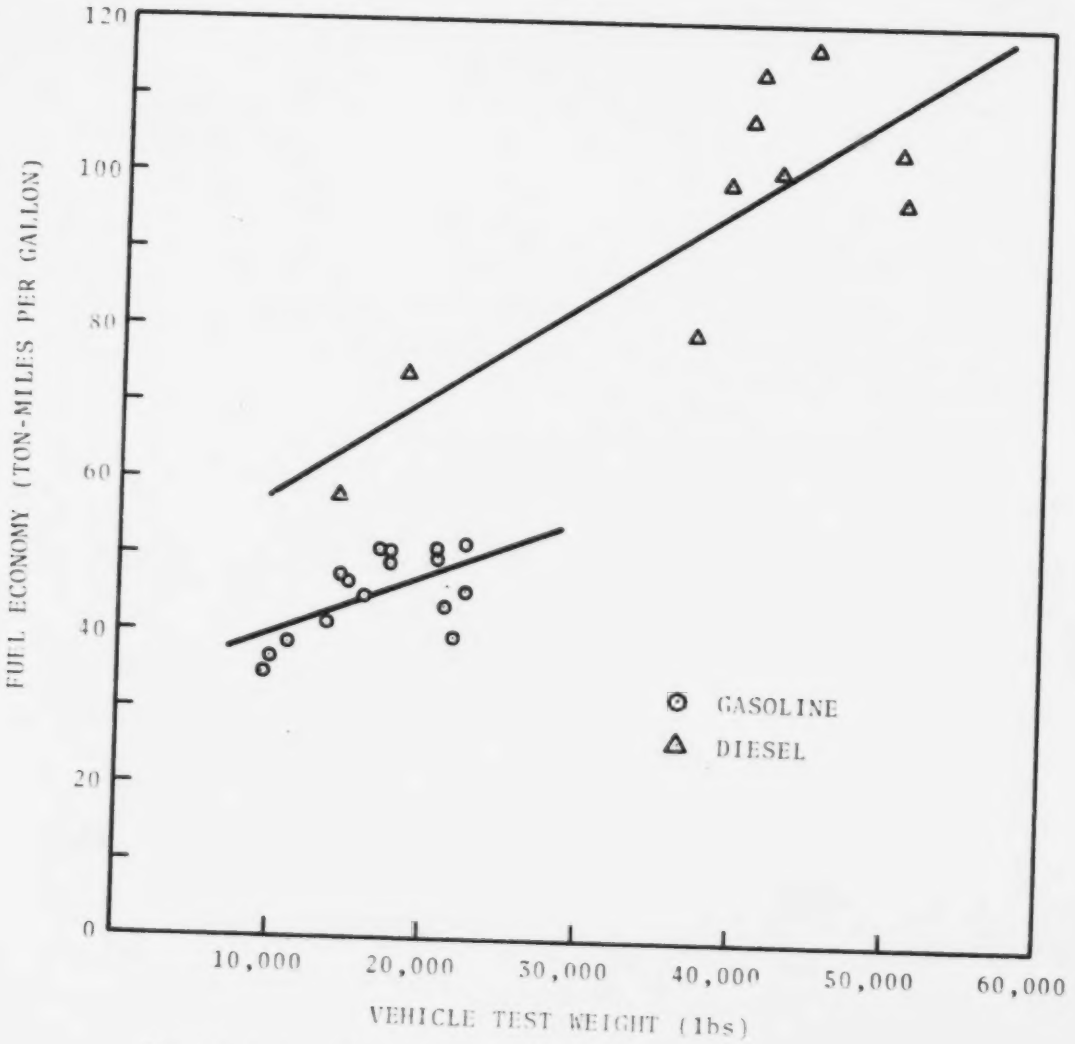

Figure 3-3. Gasoline and Diesel Truck Road Route Fuel Economy

A diesel powered truck is more expensive than a comparable size gasoline powered truck. The heavier weight diesel engine requires heavier suspension and structural members which adds noticeably to the overall weight and cost of the truck. Summarized in Table 3-9 are representative retail cost figures for several different production trucks in which both gasoline and diesels are available. As seen in this table the increase in cost of the trucks with a diesel engine instead of a gasoline engine may be between 20 and 50% depending on the size of the vehicle.

The introduction of diesel engines, in part due to production capacity limitations, is not expected to impact weight Classes III through V. However, essentially complete adoption of the diesel engine is expected in weight Class VIII. Weight Class VI and VII vehicles powered by diesel engines will increase from 2% to 28% and 34 to 77% respectively. The diesel engine manufacturing industry is currently operating at capacity and producing approximately 500,000 engines per year. 32% of these engines (160,000 units) are being installed in the new truck and bus fleet. Projected capacity in 1980 is one million engines per year with 35% (351,000 units) committed to new trucks and buses. Construction equipment, marine, stationary power sources and the export market account for the remaining production capacity.

TABLE 3-9 DIESEL ENGINE SUBSTITUTION COSTS

	Diesel Powered Vehicle Cost	Gas Powered Vehicle Cost	Incremental Cost due to Diesel Powerplant	Diesel Vehicle Divided by Gas Vehicle Cost
City Delivery (27,000#GVW)	$ 9,737	$ 6,337	$3,400	1.53
Cab-over Tractor (30,000#GVW)	$16,163	$12,663	$3,500	1.28
Fuel Delivery (33,560#GVW)	$22,000	$18,000	$4,000	1.22

Source: International Harvester Bulletin 261, September 1973

The durability and reliability of diesel engines in heavy duty and medium sized trucks is higher than that of gasoline engines. Fleet owners* report substantially greater mileage between major engine repairs for the diesel engine. A summary of fifteen fleet reports showed an average of 223,000 miles between major engine repair occurrences for the diesel engine. A comparable figure for gasoline engines would be 100,000 miles.

Table 3-10 is a summary table of the fuel economy improvement resulting from substituting a diesel engine for a gasoline engine.

3.3.1.2 Turbocharging a Diesel - A turbocharger is a device which combines a turbine driven by engine exhaust gases with a compressor to increase the air flow into the engine combustion chamber.

Turbocharging enhances the efficiency of a diesel engine in two ways. First, the turbocharger increases the amount of air entering the engine combustion chamber thus permitting more fuel to be injected and more power to be generated per piston stroke. Equivalent power can be achieved from a smaller or a slower running turbocharged engine than from a naturally aspirated engine. Thus engine friction and other mechanical losses can be reduced as a result of turbocharging. The second benefit derives from the increased inlet air pressure and inlet air temperature which assures more complete combustion and reduce the so called ignition time delay losses. The increased inlet air temperature and pressure also increases the energy release upon combustion due to higher energy levels of the air/fuel mix at the onset of combustion.

The fuel economy improvement for the diesel engine is somewhat sensitive to the type of driving mode as shown in Table 3-11. As the engine load increases, the improvement effect of the turbocharger decreases since ignition time delay losses[3] normally

*Statistics taken from maintenance figures available in Fleet Week 1974

TABLE 3-10 FUEL ECONOMY IMPROVEMENTS AND PRODUCTION RESTRAINTS RESULTING FROM SUBSTITUTING A DIESEL ENGINE FOR A GASOLINE ENGINE

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	20 - 40%	38%	12 - 24%	38%	4 - 8%
Short	10 - 20%	51%	4 - 9%	95%	4 - 8%
Long	5 - 40%	86%	1 - 3%	99%	1 - 3%

TABLE 3-11 FUEL ECONOMY IMPROVEMENT (%) BY TURBOCHARGING A DIESEL ENGINE

Vehicle Class	Driving Cycle			Source:
	Local	Short	Long	
Heavy VIII	-	-	4.2	Cummins
Heavy VIII	-	-	7-10	International Harvester
Medium VI	5-10	5-10	0-10	C.A.V., Limited
Light Heavy VII	0-10	0-10	0-5	C.A.V., Limited
Bus - Transit	0-10	0-10	-	Author's Estimate
Bus - Intercity	-	-	0-5	Author's Estimate

Sources:

Cummins Engine Co., "Trucker's Guide to Fuel Savings, Bulletin 952880, 10/73

Wallace, R. E., International Harvester, 120 day study Public Docket response of August 15, 1974

Kellett, D. K., "Experiments on Turbocharged Diesel Vehicles," C.A.V., Ltd.

disappear at higher loads. Table 3-12 is a summary of the fuel economy improvements expected from a diesel engine.

The cost of a retrofit turbocharger kit for a diesel engine is approximately $800 from the original equipment manufacturer. Installation labor costs for a turbocharger kit will probably exceed $200. Diesels of the heavy duty type can be and very often are purchased with turbochargers as original equipment.

The present demand for turbocharged diesel engines already exceeds the supply in most cases and it seems that the major limitation is the diesel engine production and not the capacity to build turbochargers. This is evidenced by the fact that there are two or more major component manufacturers of turbochargers and at least one major engine manufacturer building turbochargers resulting in a plentiful supply.

3.3.1.3 Derated Horsepower - Some fleet managers, when ordering vehicles for their fleets, specify derated engines; that is engines with fuel injectors calibrated to deliver less fuel than that required to produce maximum rated or designed engine horsepower. By specifying this option these managers feel that engine durability will be improved because of reduced engine power levels thereby reducing their maintenance costs. An accrued side benefit to this action is an improvement in fuel economy. This, of course, can only be applied where available vehicle power is more than required to meet route gradeability* and speed requirements. Also, any significant increase in shifting frequency will add to driver fatique and might increase vehicle (primarily clutch) maintenance. Route simulation tests conducted by Cummins Engine Company show, for a 70,000 pound GCW vehicle, that a 12% deration of engine maximum horsepower would result in fuel savings of 4.8% for a vehicle geared to cruise at 61 mph in long haul operations. According to

* Gradeability is the excess power available to climb grades at required road speed.

TABLE 3-12 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM TURBO-CHARGING DIESEL ENGINES

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	5%	8%	1%	38%	< 1%
Short	5%	29%	1 - 2%	95%	1 - 2%
Long	3 - 5%	45%	1 - 2%	99%	1 - 2%

the route simulation this fuel saving would result in an increase in trip time of 3.5% (17 minutes on an original 8-hour trip). With the national speed limit at 55 mph, the effect of derating on trip time would be small. Initial vehicle cost with this option would be unchanged or very slightly reduced, and where engines and transmissions were properly matched for the intended route, operating and maintenance costs would also be reduced. Table 3-13 is a summary of the fuel economy improvements expected from the derated horsepower option.

3.3.1.4 Reducing Engine RPM - Diesel engine manufacturers typically rate engine speed to the point of governor* actuation; about 10% above the engine speed for best fuel efficiency. Under highway cruise conditions, many drivers use the engine governor as a vehicle speed control device. This is accomplished by using the maximum throttle setting and allowing the governor to restrict fuel flow to match road-load and aerodynamic forces on the vehicle. In effect, this allows the engine to continuously operate at a speed higher than rated by the engine manufacturer, and in a range even less efficient than the rated speed conditions.

The intent of reducing engine speed by governor recalibration is to force the vehicle driver to operate the engine closer to its point of best fuel efficiency. At least one heavy duty engine manufacturer has recognized this problem and is contemplating a reduction in engine speed ratings across his product line.

The difficulty with reducing governor setting is that some additional shifting will be required with attendant additional wear on the drive train components and driver. A better solution would be to motivate drivers to operate their vehicles at lower engine speeds. Route simulation data from the Cummins Engine Company shows that for a slight increase (0.7%) in trip time, fuel savings of as much as 6% can result. The same considerations are even more applicable to governed gasoline engines because gasoline engine fuel consumption is typically more engine speed/load

*A governor is a device for automatically controlling the maximum speed of an engine by limiting fuel flow.

TABLE 3-13 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM DERATED HORSEPOWER DIESEL ENGINES

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	2 - 5%	--	2 - 5%	38%	1 - 2%
Short	2 - 5%	--	2 - 5%	95%	2 - 5%
Long	2 - 5%	50%	1 - 3%	99%	1 - 2%

sensitive than is a diesel engine. Table 3-14 is a summary of the fuel economy benefits expected from reduced engine speed.

3.3.2 GASOLINE FUELED ENGINES (Spark Ignition)

3.3.2.1 Lean Burn - The term lean burn applied to spark ignited gasoline engines is a generic class of fuel economy improvement. Most innovations in spark ignited gasoline engines are in fact attempts at reducing the fuel to air mixture ratio. This in general provides the lowest fuel consumption for a specific driving demand. Several specific approaches have become associated with the lean burn concept, some of them are listed below:

Concept	Description
Ethyl Corporation Detroit, Michigan	High velocity variable venturi carburetor, manifold reactor modulated exhaust gas recirculation and exhaust port inserts for heat retention, a highly developed concept. The high velocity breaks the fuel particles into finer mist for more even mixture. This is accomplished by varying the venturi so as to maintain high velocity. This also permits better regulation and fuel flow.
Shell International Petroleum Co. Ltd. London, England	Vaporizing carburetor employs a conventional carburetor followed by a heating device utilizing exhaust gas heat, to vaporize gas and create a more uniform mixture.
Dresser Industries, Inc. Santa Ana, California	High velocity variable venturi carburetor.

TABLE 3-14 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM REDUCED DIESEL ENGINE SPEED

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	7 - 10%	--	7 - 10%	38%	3 - 4%
Short	7 - 10%	--	7 - 10%	95%	6 - 10%
Long	7 - 10%	--	7 - 10%	99%	7 - 10%

Automotive Controls Corp. El Paso, Texas	Utilizes ultrasonic fuel atomizer
Bendix	Intake Valve Throttling

The fundamental issue of providing lean burn spark ignited engines is not the limitation of the fuel metering device to lower the fuel-to-air mixture ratio but the ability of the fuel metering and distribution systems to provide a uniformly mixed fuel/air mixture ratio to the combustion chamber. While the overall mixture admitted to the cylinder may be well within the flammability limits of gasoline/air combustion, areas in which a scarcity of fuel will occur may inhibit proper combustion.

Therefore lean burn concepts are those innovations which increase the uniformity of the fuel/air composition so that fuel starved pockets are avoided. With the elimination of these ultra-lean pockets, fuel enrichment, generally necessary to ensure proper combustion, is not required, thus resulting in improved fuel economy and reduced pumping losses.

For a comprehensive discussion of the individual lean burn concepts see Reference 4. Suffice it to say that the five lean burn concepts represents a small portion of the entire class of fuel metering and fuel distribution improvements aimed at permitting leaner operation of the engine. When taken as a class, improvements between 5 and 10% may be realized. The summary range of improvement is given on the bottom line of Table 3-15 and serves as the estimate of the improvement in fuel consumption which may be expected with lean burn concepts.

Some hardware concepts associated with lean burn are substantially different from existing fuel metering and distribution equipment. The added complexity of design may cause subsequent problems with reliability or durability.

Except for the advanced design carburetors basically providing more accurately controlled air/fuel mixture ratios, but

TABLE 3-15. IMPROVEMENT IN GASOLINE ENGINE FUEL ECONOMY (%) WITH LEAN BURN CONCEPTS

	Driving Mode			
Type	Local	Short	Long	
Ethyl Corp.	5-10	5-10	5-10	
Shell	20-40	-	8-10	
Dresser	5-10	-	-	
Automotive Controls Corp.	5	-	-	
Intake Valve Throttling	5.5	5	7	
	> 1-10	> 1-5	> 1-7	Authors' estimates

Sources

- Ethyl Corporation, Detroit, Michigan
- Shell International Petroleum Co., Ltd., London, England
- Dresser Industries, Inc., Santa Ana, California
- Automotive Controls Corporation, El Paso, Texas
- Authur D. Little Report to DOT/EPA "A Study of Technological Improvements in Automobile Fuel Consumption" DOT-TSC-627

not achieving the full benefit that a lean burn concept could achieve, the devices making up this class of improvements are mostly in the feasibility or development stage. Table 3-16 is the summary table for this option.

3.3.2.2 Fuel Injection - Most gasoline engines built for the American market utilize a carbureted fuel metering system. In this system, the air and fuel are mixed at a central location for distribution by appropriate manifolding and valves to the combustion chambers. The advantage of a carbureted system is its low cost and easy installation. The central mixing of air and fuel eliminates the need for duplicating critical air/fuel metering mechanisms for each combustion chamber. An inherent drawback to the carbureted system is its inability to provide a uniform mixture of atomized fuel and air to the individual combustion chambers under all required operating conditions. Fuel often condenses from the atomized mixture on intake manifold walls resulting in unequal and insufficient distribution to the individual engine cylinders. This unequal distribution can cause lean fuel zones and subsequent misfiring unless compensating excess fuel is provided by the carburetor. With fuel injectors for each cylinder, the distribution problem and thus the excess fuel requirement can be eliminated.

Fuel injectors may be placed in the intake port of each cylinder to spray fuel through the valve opening during the engine intake stroke or in the engine cylinder head to inject fuel directly into the combustion chamber. Intake manifold injection is generally preferred for gasoline fuel engines since the injector need not be exposed to the high temperatures and pressures that occur within the combustion chamber. The equipment is therefore simplified and lower in cost.

A summary of the fuel economy improvement that may be expected with fuel injection in a gasoline spark ignited engine is given in Table 3-17. Two sources are given; the first is a study by Freeman and Stahman in 1965, and the second a study by Bendix reported in 1972. In each case a variable timed intake port

TABLE 3-16 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS FOR LEAN BURN GASOLINE ENGINES

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980 (a)	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	>1 - 10%	--	0 - 10%	62%	0 - 6%
Short	>1 - 5%	--	10 - 20%	5%	.5 - 1%
Long	>1 - 7%	--	0 - 2%	1%	<1%

(a) These percentages reflect the portion of total 1980 vehicle production incorporating gasoline engines, since lean burn concepts are limited to these engines. It has been assumed that the preference would be to substitute diesel engines.

TABLE 3-17 COMPARISON OF FUEL ECONOMY IMPROVEMENT ESTIMATES FOR GASOLINE ENGINES WITH FUEL INJECTION

Urban	Short	Long	Source
5 - 11%[1]	5 - 10%[2]	9 - 10%[3]	Freeman & Stahman
0 - 10%	0 - 5%	5%	Bendix[4]
0 - 10%	0 - 7%	5 - 10%	Authors Estimates

Source:

1. Freeman and Stahman, "Vehicle Performance and Exhaust Emissions-Carburetion versus Timed Fuel Injection": SAE 650863, Nov. 1965.
2. IBID: Condition: 40 mph
3. IBID: Condition: 60 mph
4. Bendix, "Control of NO_x Emissions from Mobile Sources", AP 72 Report to EPA No. 6213.

injection system was used. In the Bendix study the injection timing and ignition timing were adjusted to provide reduced engine emissions while the Freeman and Stallman study optimized the fuel consumption. Since the Freeman and Stahman study was prior to the Clean Air Act and subsequent stringent emission controls, the percent gain by fuel injection is greater than that experienced in the Bendix system which reflects emission control constraints.

Data reported by Bendix on the level of emissions from a 429 cubic inch displacement gasoline engine are given in Table 3-18. While the intent of the Bendix study was to meet light duty emissions standards, data were reported on a comparative horsepower basis and are therefore applicable to heavy duty service. Though they do not compare directly to any federal test procedure, they are used here for an assessment of relative performance. As seen in this table, fuel injection reduces the CO emissions as would be expected from leaner mixtures, since CO is a result of a lack of sufficient oxygen during the combustion process.

Based on a 5% reduction in fuel consumption in city and urban driving, fuel injection is only a borderline cost effective option. This is based on an estimated added cost of $225.00 to the vehicle. Table 3-19 is a summary table for the fuel injection option.

3.3.2.3 Turbocharging - A turbocharger is an exhaust gas driven air compressor. Turbocharging increases the ability of the engine to deliver power by increasing the quantity of air available for combustion. If applied properly, it will also provide an increase in fuel economy.

A smaller displacement, turbocharged engine can provide the same maximum power output as a larger naturally aspirated engine and will operate more efficiently under cruise conditions because of higher cylinder pressures.

Over a given driving cycle a turbocharged engine will achieve higher temperatures and pressures in the combustion chamber than a comparably powered larger sized naturally aspirated

TABLE 3-18 COMPARISON OF FUEL ECONOMY FOR FUEL INJECTION VERSUS CARBURETED ENGINES

Engine Conditions		Carbureted Engine			Electronic Fuel Injection			
			G/bhp-hr			G/bhp-hr		
RPM	Torque	BSFC	HC + NO_x	CO	BSFC	HC + NO_x	CO	% Improvement
1200	45	.893	6.2	12	.841	18	10.7	5.8
1200	100	.535	7.7	7	.531	15.8	5.1	.7
2000	70	.649	13.7	7.6	.614	10.0	7.3	5.3
2000	180	.432	16.4	5.2	.432	8.6	6.4	0
640	35	1.250	2.7	15	1.114	8.1	13	10.8

Source: Bendix Control of NO_x Emissions from Mobile Sources, April 72 Report to EPA No. 6213.

NOTE: Test engine displacement: 429 cubic inches; compression ratio: 10.5 to 1.

TABLE 3-19. FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM FUEL INJECTION - GASOLINE ENGINE

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980 *	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	0 - 10%	--	0 - 5%	62%	0 - 3%
Short	0 - 7%	--	0 - 3%	5%	<1%
Long	5 - 10%	--	0	1%	<1%

* These percentages reflect the portion of total 1980 vehicle production incorporating gasoline engines, since lean burn concepts are limited to these engines. It has been assumed that the preference would be to substitute diesel engines.

engine. This means a higher thermal efficiency and better fuel economy.

For turbocharged gasoline engines provisions must be made to limit peak cylinder pressures and temperatures to prevent exceeding the knock limit of the air/fuel mixture.

Knock occurs when a gasoline mixture self ignites due to excessive cylinder temperatures and pressures. Knock or preignition results in prematurely high cylinder pressures during the compression stroke causing power loss and possible engine damage. To overcome this, the compression ratio of the engine may be reduced so that pressures and temperatures do not exceed the fuel/engine knock limit.

A summary of the percent improvement in fuel consumption which a turbocharger can provide is given in Table 3-20. The improvement shown in the Schwirkert & Johnson study and the Garrett work is based on the fuel economy advantage of a reduced size turobcharged engine to a comparable power level non-turbocharged engine.

Table 3-21 shows the effect of turbocharging on emissions as measured by the Federal 13 mode test procedure for heavy duty engines. The increased cylinder temperatures and pressures as a result of turbocharging increases the NO_x emissions. The addition of EGR (Exhaust Gas Recirculation) can substantially reduce the level of NO_x emissions.

Retrofit of an existing gasoline engine with a turbocharging kit cost approximately $650.00 in 1971. This kit included an exhaust gas waste gate control to limit peak pressures to prevent knocking. Actual cost figures for turbocharging units as part of the production line vehicle costs are not presently available. However, it appears that the added initial cost would be somewhat lower if turbochargers were produced on a volume basis.

The reliability and durability of a turbocharger may be considered fairly good since experience with turbocharged diesels shows that most turbochargers have a life expectance in access of 100,000 miles if properly lubricated. Table 3-22 is a summary table of the turbocharging option.

TABLE 3-20 PERCENT IMPROVEMENT FOR TURBOCHARGED GASOLINE ENGINE OVER NATURALLY ASPIRATED GASOLINE ENGINES

DATA SOURCE	LOCAL	SHORT	LONG	SCHOOL BUS LOCAL
SCHWEIKERT & JOHNSON	25[1]	20[2]	17[3]	25[4]
GARRETT		20[5]		
AUTHOR ESTIMATE	15 - 20	15 - 20	10 - 15	

Source:

1 - Schweikert & Johnson, "A Turbocharged Spark Ignition Engine with low Exhaust Emissions and Improved Fuel Economy", SAE 730633.

NOTE: Turbocharged 307 CID Engine versus naturally aspirated 450 CID.

Local is equivalent to engine at 1200 RPM and 30 BMEP.

2 - IBID, 40 mph equivalent

3 - IBID, 50 mph equivalent

4 - IBID, same as (1) above

5 - Garrett Airesearch, Briefing for DOT, February 6, 1974, (a turbocharged 250 CID versus 350 CID unturbocharged engine).

TABLE 3-21 COMPARISON OF EMISSIONS OF TURBOCHARGED AND NON-TURBOCHARGED GASOLINE ENGINES ON 13-MODE CYCLE

CONDITION	EMISSIONS IN GR/BHP-HR	
	$HC+NO_x$	CO
TURBOCHARGED W/O EGR (307 CID)	9.18	1.12
NATURALLY ASPIRATED W/O EGR (450 CID)	7.98	1.22
TURBOCHARGED W EGR (307 CID)	3.5	1.19
NATURALLY ASPIRATED W EGR (450 CID)	3.0	1.38
FEDERAL HEAVY DUTY VEHICLE EMISSION CONTROL REQUIREMENTS - HIGHWAY GASOLINE AND DIESEL	16.0	40.00

SOURCE: Schweikert & Johnson, MTU, "A Turbocharged Spark Ignition Engine with Low Exhaust Emissions and Improved Fuel Economy", SAE 730633.

NOTE: EGR - exhaust gas recirculation

TABLE 3-22 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM TURBOCHARGING GASOLINE ENGINES

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980*	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	15 - 20%	--	15 - 20%	63%	9 - 12%
Short	15 - 20%	--	10 - 15%	5%	<1%
Long	10 - 15%	--	10 - 15%	1%	<1%

*These percentages reflect the portion of total 1980 vehicle production incorporating gasoline engines, since turbocharging concepts are limited to these engines. It has been assumed that the preference would be to substitute diesel engines.

3.3.2.4 Stratified Charge Engine Substituted for Gasoline Engine - The stratified charge engine is designed so that combustion takes place in two stages. In the first stage, a small amount of slightly rich fuel mixture is ignited and permitted to spread into the leaner body of the charge. The initial rich mixture guarantees ignition. The body of the charge is lean, so that the net effect of the stratified charge is to permit the combustion of lean mixtures while avoiding misfire and reducing certain emissions.[5] The stratified effect can be accomplished by either direct injection into the main combustion chamber as in the Texaco combustion process, or in a small separate chamber called the prechamber. In the prechamber engine, as the initial rich mixture burns it spreads through an opening into the main combustion chamber. In the Texaco process, a rich mixture is created near the spark source and subsequent combustion spreads to the remainder of the cylinder containing the leaner mixture. In either case the stratified charge engine permits operation at overall lean fuel/air mixture ratios.

Stratified charge offers several advantages over the conventionally carbureted engine. Because of the stratification the average fuel/air mixture ratio can be lean while providing a fuel rich mixture in the ignition zone to guarantee ignition. Stratified charge combustion processes which utilize direct injection into the cylinder also permit increased compression without attendant problems in ignition or knock. The injection of fuel can be made late in the compression stroke, thereby reducing the possibility of preignition.

A test of the effect of stratified charge was performed at Ford on a 534 CID heavy duty truck engine. The engine, installed in a truck tractor chassis, was tested at a gross combined vehicle weight of 70,000 pounds. The stratified charge engine, at a 9:1 compression ratio showed fuel economy gains of about 15% relative to the 7:1 compression ratio production engine. A comparable diesel engine showed nearly a 30% improvement over the production gasoline engine.

Further studies by Ford suggest that a fully stratified charge engine could show between 20 to 23% fuel economy gains relative to a conventional gas engine. Studies at Texaco show a 27% gain in fuel economy measured via the Federal Test Procedure on a small displacement gasoline engine.

Stratified charge emission results from many sources indicate that such engines can comply with the 1975 emission standards for automobiles. There appears to be no constraint that would prevent a similar engine from meeting heavy duty vehicle standards.

The acceptability of the stratified charge engine for heavy duty truck use will be limited by competition with a comparable sized diesel engine. The diesel engine in keeping with current practice will be designed for longer life and greater durability. To meet these limits the potential cost advantages of the stratified charge concept over an equivalent diesel engine would be minimized. The availability of injectors* for heavy duty stratified charge engines would be a limiting factor in the rates at which production vehicles could be made available. Table 3-23 is a summary table of the stratified change option.

3.3.2.5 Summary of Spark Ignition Engine Improvements - The evaluation of the above improvements indicate that fuel economy gains are possible. However, as shown in Section 3.3.1.1, the advantage of a diesel engine substituted for gasoline engines outweigh the advantages of gasoline engine improvement options.

Secondly the gas engine improvements are primarily being developed for passenger automobiles and light duty trucks and would only be applicable for Class III, IV and V vehicles.

Because these improvements are only in the development stage they would not be available for Class III by 1980. Furthermore, these improvements would not be acceptable to the commercial user until after extensive proven experience on automobiles and light duty trucks.

*Note: The Honda CVCC does not require injectors, though 2 carburetors and 2 induction systems are required.

TABLE 3-23 FUEL ECONOMY IMPROVEMENT RESULTING FROM STRATIFIED CHARGING - GASOLINE ENGINE

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	10 - 30%	0%	10 - 30%	0%	0%
Short	10 - 15%	0%	10 - 15%	0%	0%
Long	5 - 10%	0%	5 - 10%	0%	0%

3.3.3 Opimized Cooling System Using Modulating Fans

One of the powered "accessories" found on all trucks and buses is a cooling fan. The inefficiency of current cooling system in general lends credence to major redesign and improvements though component change. A typical heavy duty truck will turn a 26 to 28 inch diameter stamped sheet metal fan in order to provide specified cooling under maximum torque and/or maximum horsepower conditions as determined under engine manufacturers procedures at very low vehicle speed and low ambient wind conditions. A cooling system must be sufficiently well designed and of a sufficient capacity to provide cooling under these extreme conditons when ambient temperatures are 125 degrees fahrenheit or higher. These standardized tests and procedures are described for example in reference 6.

The root of these engine manufacturer derived specifications appears to be the maintenance of engine oil temperatures below 250° Fahrenheit. The so called air-to-boil temperature* test (ATB) is a standard measure of the adequacy of cooling for a particular engine installation. If the air-to-boil temperature is not sufficiently high the warranty of the engine will be voided. In the process of meeting the air-to-boil specifications set by the engine manufacturers, the original equipment manufacturers will typically install the largest fan easily mounted within the chassis. When higher horsepower engines are installed in a particular chassis, fan speed is typically increased by changes in pulley ratio in order that higher air flows through the radiator core can be achieved to increase cooling. The increased fan speed produces a significant increase in parasitic horsepower of the fan as well as a significant increase in noise. Present practice finds fan drive ratios at 1.2-1.5 times the engine speed. For engines typically governed at 2100 rpm, fan speeds will be 2500-3150 rpm. Furthermore, an increasing number of original equipment manufacturers are finding

*Air-to-boil temperature meaning the temperature of the inlet air to the radiator at which boiling of the coolant will occur.

their chassis to be power limited due to noise regulations which in turn limits their ability to continually increase fan speed.

Required fan horsepower is a cubic function of engine speed under these drive arrangements. Horsepower consumption by a typical 28 inch diameter stamped sheet metal fan ranges from 20-30 horsepower depending upon fan drive ratio and governed engine speed as well as the particular installation.

Various technologies are reaching the fore that point at improvements in efficiency of the cooling system for purposes of reducing noise. These improvements also have a direct impact upon the energy consumed by the fan, hence will produce significant fuel savings for the truckers. The improvement of the environment in which the fan operates as delineated in reference 7 indicates that by proper selection of shroud design, spacing between radiator and fan and engine, and tip clearance between the fan and the shroud, that for a completely equivalent cooling ability, the fan speed can be reduced by 25% which saves more than 50% of the power needed to drive the fan. When such modifications are designed into a new vehicle, fuel savings of 5% or more can be anticipated. No increase in vehicle tare weight, no safety implication, no detrimental ramifications of any sort are anticipated from such cooling system design optimizations. Further improvements in the cooling system of this nature would improve the tare weight posture of a new vehicle through the replacement of radiator shutters by full blocking thermostats, adoption of more efficient radiator cores to work at higher temperature with pressurized coolant, and possibly the use of lighter fans since such high centrifugal loads would no longer be sustained due to lower fan speeds.

The use of flexible fans which provide a variable blade pitch as fan speed is increased have been suggested by one fan manufacturer. Power savings through the use of such flexible fans is claimed to be as high as 5-15 horsepower but caution must be exercised to ensure that such savings are not at the expense of adequate cooling.

A very likely approach by an original equipment manufacturer to conserve fuel by cooling system improvements would be the adoption of one of the numerous temperature actuated, variable speed fan-drives that are presently on the market or planned for introduction. The paradox involved in the use of such temperature actuated fan drive systems is that while the engine manufacturers cooling requirements must be met to sustain warranty conditons, the vast majority of the operations that will be experienced by the engine will require no cooling fan drive at all. Thus the parasitic horsepower requirements of a fan can be eliminated when such power is in fact not needed to co l the engine. Various fan-drive approaches from air actuated dry clutch system, viscous drive systems, through completely variable speed hydraulic drive systems have been engineered and marketed. Reference 8 lists the present known sources of variable speed fan drive actuation systems.

The Department of Transportation initiated a series of field evaluations of various types of demand fan drive systems. Twenty five units have been placed in the field utilizing both the simple on/off dry clutch type through the fully modulated fan drive system. Results of these tests indicate that, through a typical year of operation, total "on" time is 5% of the engines hours or less. Of this experienced "on" time, only 2-3% occurs when the engine is operating above 1600 rpm, a level at which significant power would be absorbed by the fan. These tests, conducted for purposes of verifying noise control approaches, are wholly appropriate to the question of fuel economy. The indications are clear that the fan horsepower presently being consumed could be saved 97-98% of the time. Thus, with typical large trucks up to a 10% percent fuel saving could result. Table 3-24 is a summary table of this option. Present operators of fan clutches are indicating 5-10% fuel economy improvements without fuel system changes as evidenced by submissions to the study group from International Harvester, Horton Industries, Inc., Rockford Clutch Division of Borg-Warner and Switzer Division of Wallace-Murray Corporation.

TABLE 3-24 FUEL ECONOMY IMPROVEMENT RESULTING FROM AN OPTIMIZED COOLING SYSTEM

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	4 - 7%	- 1%	4 - 7%	100%	4 - 7%
Short	6 - 9%	- 1%	6 - 9%	100%	6 - 9%
Long	7 - 10%	- 1%	7 - 10%	100%	7 - 10%

Other inputs from fleet operators indicate similar results of up to 10% improvements in fuel economy through retrofitting with such fan drive systems.

A more complex approach would be the optimization of the cooling system to the point of effecting the chassis design of the trucks involved. One example of such optimization is evidenced by the Freightliner Corporation, Powerliner series of truck cabs now being marketed with a very large frontal area radiator and large diameter clutch fan. One Powerliner was used in a prototype configuration to perform uner a Department of Transportation Quiet Truck Contract. Reference 5 indicates under a net discounted cost (NDC) approach, the savings of a demand actuated fan drive within the wide radiator version of this new truck to be some $2,595 over the life of the truck if fuel were assumed to be 30 cents per gallon. This indeed is a significant saving.

Manufacturing costs associated with the improved cooling system design are estimated to be as follow: for the minimization of fan tip speed by improved fan shrouds and optimized radiator-to-fan engine clearance, the cost of a new truck should be unchanged. Substitution of blocking thermostats for radiator shutters should result in cost savings of approximately $130 and a reduction in weight of 20 pounds. Addition of temperature controlled fan drives should increase the weight by some 10 pounds and increase the cost by some $200. Incorporation of the wide cab to permit larger radiator frontal areas will increase the manufactured cost by some $300 and will carry an incremental increase in weight of some 150 pounds.

3.3.4 Power Train

A gain in fuel economy appears possible by properly adjusting engine speed and torque to meet the road horsepower demand. This is the role of the transmission and drive axles. Improved transmissions combined with multispeed axles to best match engine conditions with horsepower demand will improve fuel economy. On the other hand, the work involved in proper operation of transmissions of large trucks may add to driver fatigue

and take away from the drivers attention to the road. Furthermore, a professional driver skill level is required to approach the fuel economy potential of multiratio manual transmission.

Two approaches available as production units are; automatic four and five speed transmissions with lock-up and the continuously variable transmission. The second development is relatively new and provides an infinite number of ratios within a set range.

3.3.4.1 Improved Transmissions; Automatic, Manual, and Continously Variable (CVT) - A four speed and five speed automatic transmission with lock-up offers fuel economy gains over two and three speed automatic transmissions presently used in transit buses. The added gear permits better automatic matching of the engine speed and torque with the horsepower demand. The lock-up feature eliminates the torque converter slip loss after it is used for startup. The lock-up is nothing more than an automatic clutch which bypasses the torque converter and its attendant power losses.

Fuel consumption figures for manual and automatic transmissions used in school buses have come from the General Motors Docket Submission. As reported by General Motors these figures actually range between 0 and 25% improvement for 11 cases, in which a 4-speed automatic without lock-up is substituted for a manual transmission. This fuel economy gain is in excess of what would be predicted from a one-for-one swapping of transmissions and indicates the influence of driver skill on the shifting of the transmission. Much of the savings must be due to poor driver use of the manual transmission, since the automatic does not improve the efficiency of the system. However, we feel that it is instructive to include this data, since it gives some appreciation to the reader of the fuel savings associated with driver aids as opposed to straightforward mechanical improvements.

Table 3-25 displays theoretically possible improvements in fuel economy of 10-20% for school and transit buses if four or five speed automatic transmissions with lock-up torque converter were

TABLE 3-25 ASSESSMENT OF POSSIBLE FUEL ECONOMY IMPROVEMENT BY SUBSTITUTING IMPROVED TRANSMISSIONS FOR CONVENTIONAL TRANSMISSIONS

Vehicle Wt Class	III, IV, V				VI				VII, VIII				School	Transit		
Replace Conventional Trans. with	%				%				%				%	%		
	Loc	Sh	L	AG	Loc	Sh	L	AG	Loc	Sh	L	AG	Loc	Loc	Sh	AG
4 sp. Auto w. Lock Up	No Improvement over present 5 speed manual				No Improvement over present 5-10 speed manual				No improvement over present 10-15 speed manual				10-15	1	15	11
5 sp. Auto w. Lock Up	"		"		"		"		"		"		---	15	20	15
C.V.T.	—	10-30	0-2	2-6	—	10-30	0-2	2-6	—	6-15	—	3-6	15-20	15-20	20-30	16-21

Sources:

ADL Report to DOT/EPA A Study of Technological Improvements in Automobile Fuel Consumption Feb. 1974. Draft Appendix Table 4-11: "4 sp. Auto Improvement over 3 Sp."

Cummins, "Partners in Power", vol. 3, no. 2.

"Fuel Economy Facts about Allison Transmissions", part of docket submission from General Motors, dated August 23, 1974, from Dr. Frederick Bowditch.

NOTE:

Loc - Local
Sh - Short
L - Long
AG - Aggregate

used. If a CVT transmission replaces a conventional transmission, fuel economy improvement may range from 0-30% depending on weight class and duty mode.

The availability and production capacity of these automatic 4-speed and 5-speed transmissions with lock-up is relatively good and a major production line of such transmissions has been available for several years, at the Detroit Diesel Allison Division of General Motors. Tables 3-26 and 3-27 are summary tables of the automatic transmission with lock-up option and continuously variable transmission option respectively.

The availability of constantly variable transmissions is presently limited to heavy duty trucks. At present Cummins Sunstrand is the only manufacturer of such transmissions for heavy duty trucks and these are not intended for long line haul applications.

3.3.4.2 Lower Axle Ratio - The purpose of a lower axle ratio for a truck is to reduce the engine speed necessary to propel the vehicle at the chosen road speed. In general, this requires higher torques to be delivered by the engine which become the limiting factor in the amount of reduction that one may reasonably attain. As the axle ratio is lowered numerically, and engine speed is brought down, the available power, after meeting the road load requirement is reduced. Therefore, the ability to accelerate is reduced. Lowering the axle ratio will reduce fuel consumption while increasing the trip time slightly. This is because the truck will suffer a loss in acceleration rate and gradability, or the ability to provide sufficient power to meet the added demand for hills or grades.

Depending on the present gearing of the vehicles, a substantail gain in fuel economy may be achieved by lowering the axle ratio and subsequently reducing the engine speed for a given operating condition. The figures that been used for estimating the percent improvement in fuel economy for a lower axle ratio reflect the 7-10% improvement in fuel consumption which was predicted for

TABLE 3-26 BUS FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM THE SUBSTITUTION OF AN AUTOMATIC FOUR SPEED TRANSMISSION WITH LOCK-UP FOR A MANUAL TRANSMISSION

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	8 - 10%	--	1%	13%	1%
Short	--	--	--	--	--
Long	--	--	--	--	--

TABLE 3-27 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM THE SUBSTITUTION OF A CONTINUOUSLY VARIABLE TRANSMISSION FOR A MANUAL TRANSMISSION

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	--	--	--	--	--
Short	10 - 30%	<1%	10 - 30%	<10%	1 - 3%
Long	--	--	--	--	--

a lower rpm setting for heavy duty trucks given in Section 3.3.1.4. The 0-10% fuel economy improvement range selected indicates that many trucks in the heavy duty and light/heavy duty weight classes are presently designed to have as low an axle ratio as possible without reducing the productivity, or trip time of the vehicle, beyond an acceptable limit. Therefore a zero to 5% fuel economy improvement has been projected for all truck sizes and use categories.

The effect of the lower axle ratio on a transit bus utilizing a three speed automatic will not be as great as a comparably sized diesel engine with a manual transmission since the higher loads on the torque converter in the automatic transmission will balance out some of the gains in lower engine speed. A value of 0-5% is assigned for this class of vehicle.

The reliability, durability and cost considerations for the lower axle ratio are not significant for the 10% rear axle ratio reduction assumed. This is available within the present line of axle ratios for all the vehicles and represents little impact on the cost of the vehicle. Table 3-28 is a summary table of this option.

3.3.4.3 Tag Axle - In many instances both of the tandem rear axles of truck tractors are driven. Power is lost in driving each axle. Cummins, in their publication Bulletin 952880 indicates that between 2 and 4% improvement in fuel economy, over the road, for the heavy duty vehicles using tandem rear axles may be experienced when only one axle is driven. With a single driven axle and a non-driven rear tag axle, a loss in maximum tractive effort will be experienced. However, except in off-road applications, poor road surface environments, and on extreme grades, the maximum tractive effort of a single drive axle is sufficient. Tag axles are readily available and are in use throughout the truck and bus industry. Table 3-29 is a summary table of the tag axle option.

TABLE 3-28 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM A LOWER AXLE RATIO

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	0%	--	0%	50%	0%
Short	0 - 5%	--	0 - 5%	50%	0 - 3%
Long	0 - 4%	--	0 - 4%	50%	0 - 2%

TABLE 3-29 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM A TAG AXLE ON CLASS VIII VEHICLES

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	2 - 5%	- 1%	2 - 5%	19%	0 - 1%
Short	2 - 5%	- 1%	2 - 5%	62%	1 - 3%
Long	2 - 5%	- 1%	2 - 5%	77%	2 - 4%

3.3.4.4 Substitution of Radial Tires for Bias Ply Tires - In the search for improved fuel economy, one area of high potential is the substitution of radial ply tires for conventional bias ply tires. The first practical pneumatic tire was patented in 1888 by John Boyd Dunlop with the primary aim to improve ride comfort but with a qualitative illustration that his inflated pneumatic tire took less effort to rotate than the solid rubber tires commonly in use at the time. The original experiment consisted of rolling a penumatic tire and a solid tire to illustrate the greater distance the pneumatic would roll for a given effort as compared to the solid tire. This was the first known rolling resistance experiment dealing with pneumatic tires. Persons of the day who were critically concerned with energy conservation (the professional cyclists of England and Ireland) quickly adopted the new tires. In the 86 years since the original development by Dunlop, many changes have been evidenced in the pneumatic tires. Research, while often crude, has led to far better understanding of the mechanisms of tire energy loss as well as the performance optimization of pneumatic tires.

Reports such as the National Bureau of Standards Monograph 121 "Mechanics of Pneumatic Tires" illustrate numerous ways to derive measures of drag force on pneumatic tires. Many of the more convenient tests incorporate shortcomings in accuracy and applicability of the data. And to date only limited data have been generated and published in the open literature which evaluate the true potential of radial tires applied to trucks and buses specifically to achieve improved fuel economy. Rolling resistance curves have been developed primarily for passenger car tires that illustrate a significant improvement (lessening) in rolling resistance when new radial tires are compared with new bias ply tires. Similar comparisons have been made in the case of truck tires as illustrated in Figure 3-4. These data indicate significant advantages from the use of radial or wide-base single tires. Experience by fleet operators* has produced economies of up to 10% in fuel consumption

*Private communication, Horst Volmer, Vice President Ryder Truck Lines, July 1974.

as a result of the application of radial ply truck tires in place of bias ply truck tires.

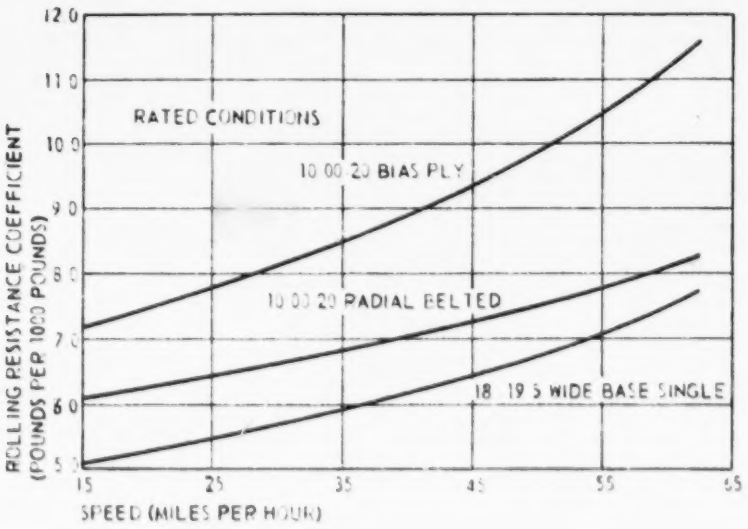

Figure 3-4 Rolling Resistance Comparison for Different Types of Tires

Source: Figure 35 from J. A. Davisson "Design and Application of Commercial Type Tires" SAE SP 344 January 1969, also note the Dunlop Report: "Fuel Consumption and Rolling Resistance of Car and Truck Tires - The Facts," dated March 22, 1974 by J. A. Turley.

In a direct comparative study, Ryder Truck Lines, Inc., ran identical tractor/semi-trailer combinations from Miami, Florida to Tampa, Florida and back on two separate occasions with tires being changed between the units to specifically observe the fuel consumption performance. The results of this experiment indicate a 9.6% improvement in fuel economy for over-the-road use of steel cord radial tires.

All of the data in the literature of radial truck tire performance has dealt with new tires and the comparative performance of such new tires. The automobile tire literature, indicates that once the tread is worn to a low level, the rolling resistance is at its lowest level for both tire types but is essentially identical for both tire types. If such holds true for truck tires, this would indicate that the 9-12% fuel economy improvements reported for radials in the literature would not be realized through the life of the tires but rather some average, perhaps half of that value, would be experienced.

Thus far the discussion has dealt with over-the-road, or high speed performance, of radial tires compared to bias ply tires. In the rolling resistance performance comparisons, the radial tire performance is quite good at low speeds. However, braking and acceleration loads as well as gradient loads imposed by stop and go city pickup and delivery driving would be a large factor in fuel economy and hence would tend to reduce the impact of lessened rolling resistance. For stop and go traffic, the tire companies generally apply a factor of half of the improved fuel economy measured over the road. One factor not considered thus far in the literature or addressed directly by any of the tire company inputs to this study is the potential savings due to reduced scrubbing forces on the radial tire when used on multi-axle vehicles. The inability of radial tires to sustain large lateral loads and hence the possible avoidance of large lateral energy losses from scrubbing would indicate a potential savings in this category.

From a noise and safety standpoint, the use of radial tires in place of crossbar bias ply tires on trucks and buses would amount to at least a 10 decibel reduction in the noise level (or halving loudness). The increased cost of radial tires is approximately offset by the increased mileage obtained with such tires. The fuel economies and reduced truck downtime resulting from radial tire use have been significant, however.

Statistics indicate that approximately 5% of the 34 million heavy duty truck tires sold annually are now radial tires; Estimates by the Goodyear Tire and Rubber Co. of future radial truck tire production are on the order of 12% of the total production in 1975 and 20% of total truck tire production by 1980. This, according to industry inputs, is about as rapid a changeover as the production equipment (and funds to pay for it) will allow. This should be contrasted to the changeover which has occurred within the past 5 years in passenger car tires, such that the U.S. industry is now capable of making about 35% of its production of passenger car ties in radial construction. Estimates by the Firestone Tire and Rubber Co. of the pace of changeover indicate an increase in automobile radial tire capacity during the next few years to the point that 65% of the production capacity will be in radial tires by 1980. Much of the impetus in the passenger tire area has been created by demands of the auto makers. Comparable changeover pressures in the truck area will not likely come from truck manufacturer demands but would flow from user demand and/or regulations. Table 3-30 is a summary table of the radial tire option.

3.3.5 Optimized Aerodynamics

Prior to the early 1950's the subject of truck aerodynamics was not seriously considered. The advent of the Interstate Highway system however, brought about an increase in the average intercity highway speed of approximately one mile per hour per year. As speed increases the aerodynamic drag force increases as the square of speed and the engine power required to overcome the drag increases as the cube of speed.

Ten years ago the University of Maryland Wind Tunnel Operations Department undertook a study of the aerodynamic drag of various truck and trailers for Trailmobile Division of Pullman Standard Inc. The series of tests (June 1953[9], October 1953[10], and April 1955[11], provided a wide variety of data on comparative drag of trucks, tractors and tractor trailers.

TABLE 3-30 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM THE USE OF RADIAL TIRES

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	0 - 3%	~0%	0 - 3%	10%	0%
Short	4 - 8%	~1%	4 - 8%	40%	1 - 3%
Long	5 - 10%	4%	5 - 10%	100%	5 - 10%

The University of Maryland tests indicated that a conventional tractor (cab behind engine) and a well-rounded 1953 vintage cab over engine (COE) tractor produce approximately the same drag when coupled to a trailer, but that a squared-off COE tractor, more nearly like today's trucks, produced 13% higher drag at 50 mph. The reports also identified 10-20% increases in drag as separation between the tractor and the trailer was increased. Reductions in drag were demonstrated when the trailer corners were rounded, when vertical braces were removed from the trailer sides, and when various extensive streamlining features were added to the tractor and trailer.

In recent years products intended to improve aerodynamics have been marketed as add-ons to trucks and trailers, and some of the new trucks and trailers have these modifications incorporated in their designs. Relatively inexpensive air deflectors for mounting on cab roof tops are available from several sources. Claims as to the effectiveness of these roof-top devices range up to 40% reduction in the power needed to overcome drag[12,13]. Add-on devices for trailers, to reduce crosswind turbulence (which was shown in the wind tunnel to be a very large contributer to drag) and to smooth trailer airflow, have been claimed to produce as much as a 37% fuel savings[12,14].

Numerous fleets have been experimenting with air deflectors on their road tractors and many have found 3-7% fuel economy improvements[14,15]. Some single unit truck applications have also been reported in the literature with equivalent fuel savings. In addition, several trucks with insufficient power to maintain legal speed limits without air deflectors reportedly were able to cruise with traffic after addition of the air deflector.

Reexamination of the conventional tractor versus the cab over engine tractor, with and without air deflectors, has lead one large trucking firm to commence replacing cab over engine tractors with air shield equipped conventional tractors[15]. Still another trucking and leasing firm is departing from its normal role as a truck user and is entering the truck manufacturing field in part because

of the energy problems being experienced. The new truck being developed has numerous features which depart from the norm but most evident is the styling which yields low wind resistance. This together with the use of wide base single tires and a non-conventional cooling system which requires little or no fan operation is expected to yield over 20% fuel savings as compared to current cab over engine tractors using the same engine[10]. Larger truck makers have explored other aerodynamic improvements such as curved windshields, but few manufacturers have decided to incorporate such design features which would increase the purchase price of the truck.

There are no identifiable safety, air quality, noise or other ramifications directly attached to the various aerodynamic improvements discussed above. It would be likely that larger improvements in aerodynamics would be possible if length limitations imposed by the various states were relaxed such that more extensive streamlining could be incorporated without reducing the cargo volume.

The benefits of any of the aerodynamic devices are dependent upon the highest speed and the average speed of operation. The maximum benefits of aerodynamic devices occur at the higher speeds where drag is the predominant retarding force on the truck. It is expected that the benefits of add-on devices and other aerodynamic improvements potentially implementable by 1980 will be nearly as great under a nationwide 55 mph speed limit as would be the case if no such speed limit existed.

No information appears to be available regarding the potential of reducing the aerodynamic drag of buses or delivery vans. The square shape of these vehicles precludes the type of aerodynamic improvements discussed above. There is no indication in the literature that any efforts save costly lengthening and streamlining are expected to pay off in this regard. Table 3-31 is the summary table of aerodynamic improvement option.

TABLE 3-31 FUEL ECONOMY IMPROVEMENT AND PRODUCTION RESTRAINTS RESULTING FROM OTPIMIZING AERODYNAMICS

Driving Mode	Vehicle Fuel Economy Improvement (mpg) for This Option	1973 New Trucks and Buses Now Using This Option	Fleet Fuel Economy Improvement if all 1980 Model Year Vehicles Use This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Local	1 - 2%	< 1%	1 - 2%	10%*	.1%
Short	3 - 5%	< 1%	3 - 5%	100%	3 - 1%
Long	3 - 10%	1 - 3%	3 - 10%	100%	3 - 10%

*This reflects cost effectiveness of adopting improvement for local use.

3.3.6 Weight and Size Optimization

3.3.6.1 Relationship Between Fuel Productivity and Vehicle Size and Weight - A sample of 220 trips by Class VII and VIII vehicles between Chicago and Kansas City[17] has shown that the following linear expression approximates the relationship between fuel consumption weight (GCW) for long haul operation:

$$GPM = .139 + .00290\ GCW$$

where GPM is expressed in gallons per mile and GCW is in tons. Assuming an average vehicle tare weight at 13 tons. This can be rewritten as:

$$GPM = .177 + .0029\ P \qquad (1)$$

where P is the payload in tons. The average truck fuel productivity (FP) is the ton-miles of payload handled per gallon of fuel used, or:

$$FP = \frac{P}{GPM}$$

From Expression (1), we obtain:

$$FP = \frac{P}{.0029P + .177} \qquad (2)$$

This relationship is expressed graphically in Figure 3-5. Also on the figure are selected data points from tests conducted by McCracken Brothers Motor Freight[17].

To a first order, the fuel economy of trucks is affected only by increased vehicle weight; air drag has been assumed to remain constant. This analyses is constrainted by legal height and width restrictions which permit weight increases only through cargo density increase or length increase. Rolling resistance is assumed to increase linearly as weight increases. The fuel economy is

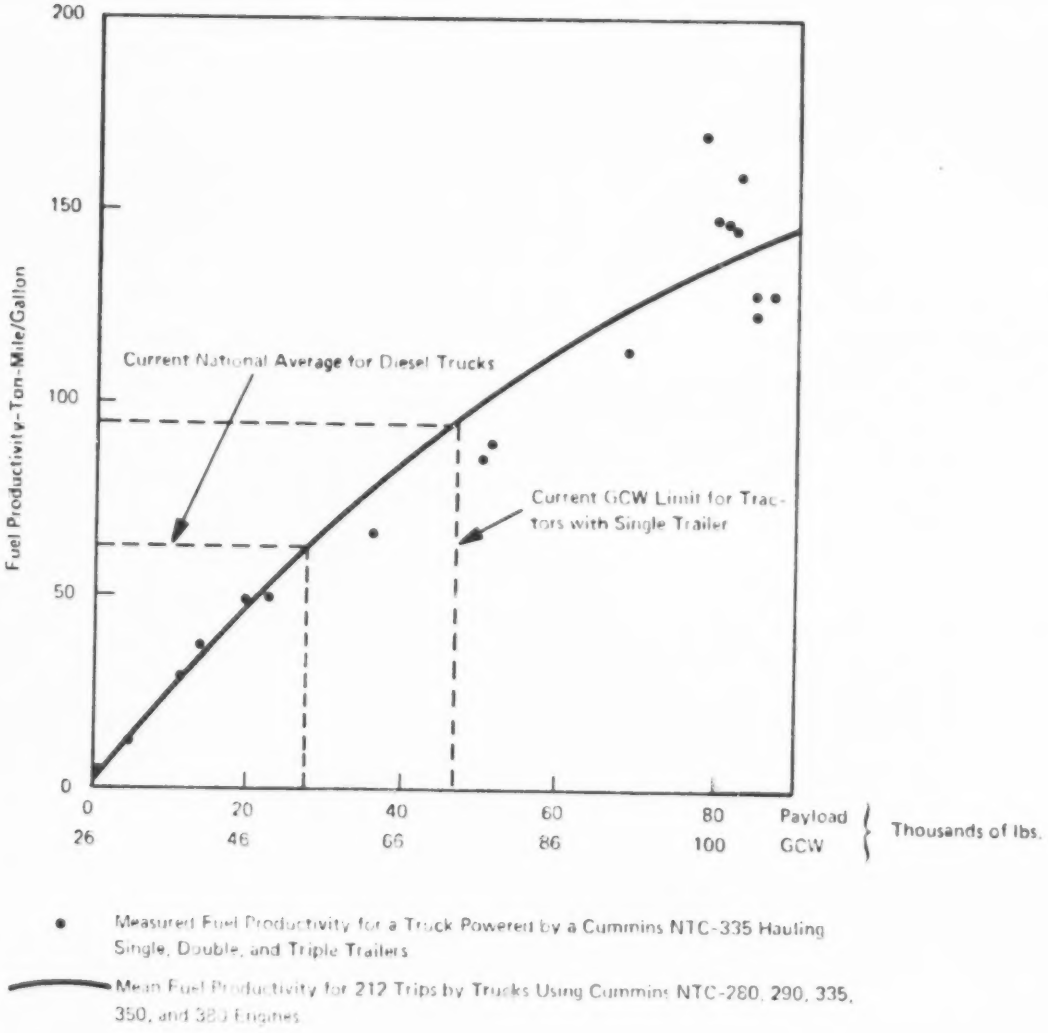

Figure 3-5 Variation of Fuel Productivity with Changes in Payload as Influenced by Vehicle Weight

sensitive only to change in the actual weight hauled; changes in weight and volume limits are felt only insofar as they affect the distribution of load weights.

The effects of changes in weight and volume limits on the distribution of loads by weight cannot presently be modeled. For one thing, the existing distribution is not known, although its mean may be obtained from ICC statistics. Similarly, there is little information on such important factors as the distribution of loads by shipping density or the generation of demand for hauling services as a function of cargo, location and time.

It is possible, however, to make some assumptions which allow an estimate of the magnitude of the possible effects. Hypothesize, for example, that payload weights (P) are presently distributed in some fashion over the interval:

$$0 \leq P \leq GCW_L - TW$$

where TW is the tare weight and GCW_L is the allowed limit on gross combination weight. One may assume that the weight and volume limits are changed in such a fashion that the shape of the distribution of P over the given interval remains the same regardless of the absolute size of the interval.* This allows one to state that the ratio of the average payload $\bar{P}$ to the limit payload P_L is a constant (note that $P_L = GCW_L - TW$):

$$\frac{\bar{P}}{P_L} = a$$

*Note that this assumption necessarily implies that weight and volume limits are changed simultaneously. This is because an increase in the weight limit alone could be utilized only by high-density cargoes (which are presently weight- but not volume-limited) whereas an increase in the volume limit alone could only be taken advantage of by low-density cargoes. Either condition would result in a change in the shape of the load/weight distribution, thus violating the assumption.

Statistics on heavy trucks[18] show that at present, $\bar{P}$ = 13.5 tons and P_L = 23.5 tons, so that:

$$a = .57$$

Using the above assumption, and Equation 2, the change in average fuel productivity for a given change in limiting gross combination weight GCW_L can be estimated. First, however, the expression for $\bar{P}$ as a function of the percent change b is GCW_L must be written:

$$\bar{P} = a[(1 + b)\ GCW_L - TW] \qquad (3)$$

The present value for GCW_L is 36.5 tons (73,000 lbs) Using $\bar{P}$ to represent payload P in Equation 2, one may solve the two equations to obtain the estimated improvement in fuel productivity FP as a function of b. This is shown in the following Table (Table 3-32).

TABLE 3-32 CHANGE IN FUEL PRODUCTIVITY AS A FUNCTION OF INCREASES IN WEIGHT AND VOLUME LIMITS

b Percent Increase In Weight Limit*	$\bar{P}$ Mean Payload (tons)	FP Fuel Productivity (Ton-mi/gal)	Percent Increase in FP
0	13.5	62.5	—
10	15.6	70.4	12.6
25	18.7	80.6	29.0
50	24.0	97.1	55.4

*Includes an increase in volume limit such that the shape of the load-weight distribution is unchanged.

Many industry comments have been received which strongly endorse the adoption of higher weight limits and acceptance of twin trailers as very effective fuel conservation moves. Table 3-33 from the American Trucking Association booklet "American Trucking and The Energy Crisis" (ATA Washington, D.C. April 1973) summarizes present federal limits and the estimate of fuel conservation which might be realized if certain new weight and length limits were adopted. Currently, legislation is before the Congress (S3934) which would increase gross combination weight limits from 73,280 pounds to 80,000 pounds. Twin trailers are still prohibited in 15 states and are limited to less than 65 feet in 5 other states. Individual state action is required to change these limits to a nationwide standard.

3.3.6.2 Effect of Changing Tare Weight - An alternative procedure to increasing weight limits would be to reduce the vehicles tare weight, thus increasing the payload capacity. The effects of such a change on fuel productivity can be computed by modifying Equation 3 above to reflect a change in tare weight:

$$\bar{P} = a[GCW_L - (1 - c)\ TW] \qquad (4)$$

where c is the percent reduction in tare weight. Using values of 36.5 tons for GCW_L and 13.0 tons for TW (typical of existing vehicles), one can solve for $\bar{P}$ as a function of c. The resulting average payload can then be substituted into Equation 2 to obtain the new fuel productivity. This is shown in Table 3-34.

TABLE 3-33 CARRYING CAPACITIES AND FUEL USE FOR TYPICAL PRESENT AND PROPOSED VEHICLE COMBINATIONS

	Present Federal Limits			Proposed Modernized Limits *		
	55-Foot Tractor Semitrailer (40 ft. semitrailer)		65 Foot Twin Trailer	55-Foot Tractor Semi-trailer (40 ft. semitrailer)	55-Foot Tractor Semi-trailer (45 ft. semitrailer)	65-Foot Twin Trailer
	Dense Freight	Light & Bulky Freight				
Gross Combination Weight (lbs.)	73,280	57,000	73,280	75,500	78,000	85,000
Number of Loads Required to Carry 1 million tons of freight	42,541	64,041	44,853	40,626	39,231	35,516
Fuel Consumption Rate — Gallons of Diesel Fuel per mile	0.238	0.205	0.230	0.243	0.246	0.255
DIESEL FUEL REQUIRED TO CARRY ONE MILLION TONS ONE MILE	10,125 gallons	13,128 gallons	10,316 gallons	9,872 gallons	9,661 gallons	9,057 gallons

* Based on "Table B" page 137, **Maximum Desirable Dimensions and Weights of Vehicles Operated on the Federal Aid Systems**, U.S. Government Printing Office, Washington, 1964.

Notes — Gross weights based on typical present and proposed vehicle configurations used in intercity service.

Number of trucks (or loads) required to move one million tons of freight computed by dividing maximum payload (in tons) into 1,000,000.

Fuel Consumption rate obtained from Cummins Engine Company's vehicle simulator computer based on a typical intercity trip (473 miles) at average road speeds (52 mph +,-) utilizing comparable current equipment.

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TABLE 3-34 CHANGE IN FUEL PRODUCTIVITY AS A FUNCTION OF DECREASES IN TARE WEIGHT (OVERALL WEIGHT LIMIT HELD CONSTANT)

c Percent Decrease In Tare Weight	$\bar{P}$ Mean Payload (tons)	FP Fuel Productivity (ton-mi/gal)	Percent Increase in FP
0	13.5	62.5	-
10	14.8	67.3	7.7
25	15.7	70.6	13.0

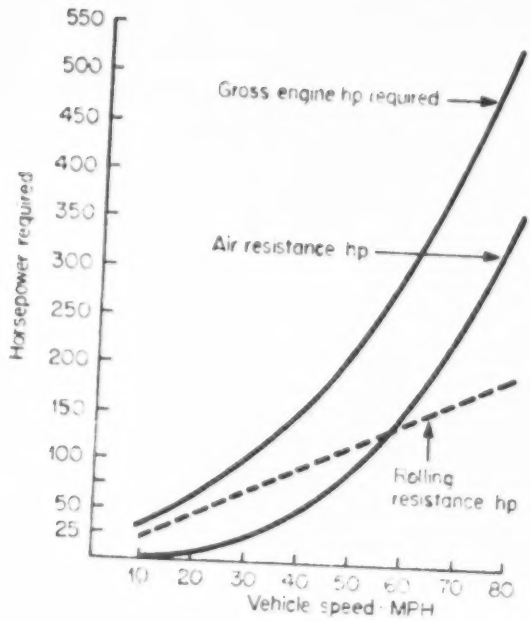
A premium has traditionally been placed upon light weight vehicles in the Class VIII over the raod category vehicles in order to maximize payload. This analysis simply sharpens the focus on an engineering problem which is a matter of keen competition between truck builders. Further reduction in vehicle tare weight solely as a result of fuel economy considerations is unlikely.

3.3.7 The Effect of Highway Speed

The 55 mile per hour federal speed limit imposed early in 1974 precipitated many claims that large trucks and buses could be operated more efficiently at higher speeds.

Many of these arguments undoubtedly were centered around total economic productivity of the vehicles (including hourly labor costs) as opposed to the motivating arguments of fuel economy only. There are any number of reliable references which clearly document the major effect speed has on truck fuel economy. Figure 3-6, for example, illustrates typical increases in aerodynamics, transmission and tire losses due to speed for a typical tractor semi-trailer.

The fuel economy impact of such rapidly rising losses are substantial. The Federal Highway Administration has just published



MPH	ARP	RRP	Gross hp
10	.7	23.8	24.5
20	5.5	47.7	53.2
30	18.6	71.5	90.1
40	44.1	95.3	139.4
50	86.1	119.1	205.2
60	148.8	142.9	291.9
70	236.3	166.8	402.8
80	352.7	190.6	543.3

Graph and chart illustrate rolling resistance power (RRP) and air resistance power (ARP) add up to total power needed to keep rig moving at steady speed. Figures are for rig with air drag coefficient of .9

Source: Ritchie, Dave, "Beat the Built-in Headwind" Commercial Car Journal, September 1973.

Figure 3-6 Power Required for a Typical Tractor-Trailer Combination (73,280 lb GCW)

a report on a series of experiments to ascertain the effects of speed on the fuel economy of six specially instrumented over-the-road tractors hauling van body semi-trailers in revenue service[18]. A grand average of these data indicate that an increase in maximum posted highway speeds to 60 mph from the present 55 mph would increase the over-the-road Class VIII fuel consumption by 5.6% and a 65 mph maximum posted speed limit would increase fuel consumption by 15%.

It has been noted in the technology sections that aerodynamics drag and rolling resistance are very sensitive to speed variations. The ability of the suggested technologies to reduce fuel consumption are likewise sensitive to the speeds at which the comparisons are made.

The improvements cited in the technology sections pertaining to radial tires and aerodynamic improvements were generally adjusted to reflect the 55 mph speed limit in the base of comparison. Should speed limits be raised, the overall vehicle fuel consumption would increase, but the relative value of aerodynamic improvements and radial tires would increase as well.

As a special adjunct of the recent speed study by DOT, driver techniques were varied to ascertain this impact on fuel consumption (see Table 3-35). Comparison runs were made operating the vehicle at or near governed engine speed versus a generally less aggressive driving mode. These driver variables are to be expected in typical service but evaluation here is for the purpose of examining the sensitivity of fuel economy with engine speed.

3.4 EMISSION IMPACT

Data are not available to calculate emission rates for all of the fuel economy technology options. Data are available which can be used to estimate quantitatively the trend in impact of several key options such as the substitution of diesel engines for gasoline engines and the effects of turbocharging. Limited data on the gasoline engine technology options have been incorporated directly in those sections. The remaining technology options are collectively treated by relating experience from passenger car

TABLE 3-35 EFFECT OF SPEED ON FUEL ECONOMY

Speed	Driving at Optimum Engine Speed	Driving at Engine Governer Limiting Speed	Decease in MPG Due to High Engine Speed
50 mph	4.86 mpg	4.25 mpg	14.4%
55 mph	4.59 mpg	4.25 mpg	8.0%
60 mph	4.25 mpg	3.95 mpg	7.6%

experimental programs and briefly analyzing how engine performance is impacted. Finally, the anticipated regulatory actions of the State of California in reducing emissions standards and the options EPA has available in the 1980 time frame are addressed.

3.4.1 Diesel Engine Substitution

EPA has gathered emissions data on both gas and diesel trucks over an urban road route. These data are summarized in Table 3-36.

These data demonstrate an overwhelming advantage for the diesel engine in terms of reducing hydrocarbon and carbon monoxide emissions by 80 to 90% respectively with a 20% increase in NO_x emissions. Additional tradeoffs when substituting the diesel include increased nuisance factors of smoke and odor normally not present in the gasoline engine.

TABLE 3-36 AVERAGE MASS EMISSIONS ON THE SAN ANTONIO ROAD ROUTE[17,18]

	HC	CO	NO_x
10 Diesel Trucks (grams/pound fuel)	3	19	14
25 Gasoline Trucks (grams/pound fuel)	14	169	10
% Reduction for Diesel	79	89	-28
% Reduction adjusted for Fuel Economy Difference*	82	90	-18

*A net 15% correction applied to diesel data combining estimated diesel mileage advantage of 25% and difference in density of fuels of 11%.

3.4.2 Turbocharging Diesel Engines

Initially, turbocharging of diesel engines was introduced to allow engine manufacturers to extract more power within their existing engine block designs by increasing the fuel-air charge density. Since parasitic losses are not significantly increased by this addition a fuel economy improvement also occurs. Besides its efficiency benefits, potential emissions benefits in reducing hydrocarbon, carbon monoxide, and smoke levels are available in advanced configurations.

Data on similar diesel engines of one manufacturer built with and without turbochargers were examined to get a first approximation of the potential impact of turbocharger substitution. These data are presented in Table 3-37 and are EPA certification data for the 1974 model year.

Although no universal conclusions can be drawn over the whole spectrum of potential turbocharger applications for new engines and for retrofit, it is apparent that when certified against a given standard, turbocharged engine emissions are at least as low as similar non-turbocharged engines.

TABLE 3-37 TURBOCHARGER EMISSIONS COMPARISON

Model	Horsepower /RPM	Grams Per BHP-Hr HC	CO	NO_x	Smoke % Accel	Lug	Peak
A	295/2600	2.6	5	7.9	9	10	12
A (Turbo)	320/2600	.8	2	8.1	9	2	17
B	240/2100	.2	5	9.4	11	12	14
B (Turbo)	350/2100	.1	2	13.2	16	5	18
C	216/3300	.7	5	9.1	10	11	13
C (Turbo)	240/3300	1.1	3	10.1	12	3	22

In addition, manufacturers have told EPA and the California Air Resources Board in recent hearings[19], that turbocharged and aftercooled engines offer the most hope in achieving low emission levels such as the 5 gr/BHP-Hr combined HC and NO_x standard proposed in California for 1977.

3.4.3 Other Engine Technology Options

Experimental programs on automobiles have resulted in considerable data on the emissions benefits of various stratified charge engine configurations and other alternative engine technology options. Within the context of light duty and tight emissions controls such technology has been shown to offer considerable benefits. Some of these demonstrated benefits would probably be realizable if such engine technology were applied to trucks, but unresolved questions regarding durability and relative benefits under less restrictive emission regulations preclude reliable estimates of the level of effectiveness.

In general, reducing power demand at a given operating condition reduces mass flow rate and corresponding mass emissions rates. However, emissions concentrations change considerably for

various speed and power levels especially on gasoline engines. Full load and no load (closed throttle) operation normally results in maximum emission concentration levels. Therefore, the reduction in power demand on the engine for a given vehicle maneuver can be expected to reduce concentration levels unless a significant increase in closed throttle operation also occurs.

For over-the-road vehicle operation at near constant power levels the impact of horsepower saving technology could be expected to reduce mass emission rates. However, on urban usage additional no load operation, expecially on gasoline engines, makes it difficult to predict any net change in emission levels.

3.4.4 Future Emissions Standards

The state of California is moving ahead with the adoption of stricter standards for heavy duty engines. EPA will soon have its own position on the adoption of interim standards for the remaining 49 states in the prior to 1980 time frame. Table 3-38 summarizes the enacted and proposed standards applicable to heavy duty engines between now and 1980.

California standards for HC, CO, and NO_x are changing in 1975 and again in 1977 to the even lower levels shown in Table 3-38. Original arguments on fuel economy impact of these proposals were made to the Air Resources Board in November 1973[19]. At that time it was argued that the 5 gram per horsepower hour combined hydrocarbon and nitrogen oxide limit, and the 25 gram per horsepower hour carbon monoxide limit, originally proposed for 1975, would result in extreme fuel penalties and restricted availability of all but a few sophisticated technology engines.

The information presented at hearings in California led to the adoption of an interim 10/30 standard for 1975 and delayed application of the 5/25 standards until 1977. Most manufacturers said they could meet the 10/30 standards with minimal fuel economy penalty over the broadest range of models.

TABLE 3-38 HEAVY DUTY ENGINE EMISSION STANDARDS

Pollutant	1974 EPA	1974 Calif	1975 EPA	1975 Calif	1977 EPA	1977 Calif	1978 EPA	1978 Calif	1983
HC							?		**
CO	40	40	40	30	40	25	?	25	**
NO_x							?		**
HC + NO_x	16	16	16	10	16	5	?	5	**
Smoke	50*	50*	50*	50*	50*	50*	?	?	**

Values listed are in grams/BHP-Hr. unless noted

*Highest level allowable in any mode of the test procedure in terms of percent opacity

**Initiation of EPA air quality based test procedures and standards

EPA is currently evaluating its position on the need and expected benefit of lowering the standards prior to the adoption of improved air quality related test procedures. The results of this investigation are not yet available. However, it has been determined that the 10/30 standard can be met with no additional fuel penalty from a 1974 baseline. In addition, diesel engine technology capable of meeting the 5/25 standards at a fuel penalty of 3% from the 1974 base has been demonstrated. The ability of gasoline engines to meet 5/25 standards without severe fuel penalties is still in doubt.

Should California decide to maintain the proposed 1977 standards, some increase in fuel consumption can be expected on those engines certified for use in California. Any proposed EPA interim standards will carefully weight needed air quality improvements against the cost of control and if a cost effective option relative to control of other mobile sources is evident, such course will be recommended. At this point, however, no specific statement on EPA interim standards and their possible impact on the fuel economy of trucks and buses can be made.

3.5 FUEL ECONOMY IMPROVEMENTS

3.5.1 Method of Analysis

In Section 3.3 the technology options were addressed as virtually isolated components. Table 3-39 has been prepared to display all of the fuel economy benefits reported on the individual options. To improve visibility of the options, these data are displayed for each of six vehicle groupings: Medium Duty Trucks (Classes III, IV, V); Light Heavy Duty Trucks (Class VI); Heavy Duty Trucks (Class VIII); School Buses, Transit Buses, and Intercity Buses. In addition, each of these vehicle groupings has been further subdivided (where appropriate) into local, short and long haul missions. An aggregate for the vehicle grouping has been derived using the 1973 fuel consumption by driving mode as the weighting factor.

Before attempting to aggregate the benefits of the best technology, the applicability of the various options must be examined. Some of the options are competitive, i.e., several options are listed for one area where only one option could be applied to any one vehicle. Other options are complementary and can be assumed to function directly with 1973 baseline as well as with 1980 new technology options. To document this, the following application combinations have been considered:

If the 1973 baseline is a spark ignited gasoline fueled engine, 1980 fuel economy improvement options include the following engine options:

- convert to diesel/diesel plus turbocharging, or
- adopt lean burn, or
- adopt fuel injection, or
- adopt stratified charge engine concepts.

As previously stated however, not only does the diesel offer the greatest fuel economy benefits, but the preliminary state of development of the spark ignited engine options appears to limit their applicability to the post 1980 period and lighter weight vehicles.

TABLE 3-39 ASSESSMENT OF FUEL ECONOMY IMPROVEMENTS FOR TRUCKS AND BUSES

The benefits of optimized cooling systems are additive and are applicable across the full range of vehicles and missions.

The power train options of reduced axle ratio and radial tires are additive. Only one transmission option may be added, where available, and the benefits of tag axles apply only where mission weights are appropriate. Aerodynamics, tare weight reduction and operational techniques are the final complementary (additive) items to the aggregate fuel economy improvement potential.

Rather than attempt to sum and weight each column for each combination of options we have attempted to assess the improvements on the basis of the four representative vehicles selected in Section 3.1. Recall that these 'representative' vehicles were selected on the basis of fuel consumed by weight-class/mission combination as shown in Figure 3-2, and as such, these four representative vehicle/mission combinations account for some 85% of the total truck and bus fuel consumption.

Two separate analyses have been performed for the representative vehicles. The first analysis assumes no production or cost restraints on the technology to be applied by 1980. The only restraint applied to this analysis is the development lead time to bring items such as the continuously variable transmissions into available status for Class VI applications. The results of this first analysis are therefore quite idealistic and represent an upper bound of potential savings.

A second analysis was performed to provide a more realistic assessment of fuel economy improvements implementable by 1980. This analysis derives from the data presented in each of the improvement option Tables (Sections 3.3.1 - 3.3.5). These reflect the estimated maximum improvement attainable by 1980 based on production capacity. The result of this analysis should more nearly reflect reasonably achievable fuel economy improvement by production year 1980.

3.5.2 Synthesized Vehicle Description and Fuel Economy Improvements

Four synthesized vehicles have been selected based on current fuel consumption and the impact on the total fuel now consumed by trucks and buses.

These synthesized vehicles may be described as follows:

1. Class VI - Local - A truck with gross vehicle weight of 19,500-26,000 pounds used for urban local driving, e.g., a small dump truck, beverage truck, pickup, and delivery van or school bus. The improvements incorporated are; turbocharged diesel engine substituted for gasoline engine, optimized cooling system and radial tires. All other improvements previously investigated do not contribute significantly to improved fuel economy and were not included.

2. Class VIII - Local - A truck with above 33,000 pounds, used for urban local driving as a pickup and delivery, 3 or 4 axle tractor semi-trailer, dump truck, cement mixer, garbage truck or transit bus. The improvements incorporated are turbocharging for the present diesel engine, including; engine fuel and speed derating, optimized cooling system, radial tires, and improved aerodynamics for beltway service.

3. Class VIII - Short Haul - A truck with above 33,000 pounds; used for short, under 200 mile trips, e.g., a four or five axle tractor semi-trailer used for freight delivery. The improvements incorporated on the diesel are turbocharging, optimized combination of engine fuel and speed derating, optimized cooling system, optimized aerodynamics, tag axles and improved transmission such as a continuously variable transmission.

4. Class VIII - Long Haul - A truck with above 33,000 pounds used for long haul shipment of freight at highway speeds, and a five axle tractor semi-trailer or tractor semi-trailer with full trailer. The improvements incorporated

on the turbocharged diesel engine are optimized cooling system, aerodynamics, radial tires and tag axle.

These vehicles are further described in Tables 3-40 through 3-43. These tables display the individual vehicle economy improvements, expected for application of the given options, as well as the more realistic (discounted) fuel economy improvements taking into account production capacity limitations.

TABLE 3-40 FUEL ECONOMY IMPROVEMENT FOR CLASS VI SYNTHESIZED VEHICLE - LOCAL DRIVING MODE
(small dump truck, beverage truck, van or school bus)

Improvement	Vehicle Fuel Economy Improvement (mpg) For This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Diesel Substitution	30%	24%	7%
Cooling	6%	100%	6%
Radial Tires	5%	10%	1%
TOTAL	41%	--	14%

TABLE 3-41 FUEL ECONOMY IMPROVEMENT FOR CLASS VIII SYNTHESIZED VEHICLE WITH DIESEL - LOCAL DRIVING MODE
(dump truck, garbage truck, cement mixer, three or four axle tractor-semi-trailer and transit bus)

Improvement	Vehicle Fuel Economy Improvement (mpg) For This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Turbocharging	5%	38%	1%
Derated RPM*	8%	100%	8%
Cooling	6%	100%	6%
Radial Tires	5%	10%	1%
Aerodynamics	1%	100%	1%
TOTAL	25%	--	17%

*In practice an optimized combination of engine fuel and speed derating would be used. The combined effect would be no more than 8%.

TABLE 3-42 FUEL ECONOMY IMPROVEMENT FOR CLASS VIII SYNTHESIZED VEHICLE WITH DIESEL-SHORT DRIVING MODE
(four or five axle tractor-semi-trailer)

Improvement	Vehicle Fuel Economy Improvement (mpg) For This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Turbocharging	5%	95%	2%
Derated RPM*	8%	100%	8%
Cooling	8%	100%	8%
Radial tires	7%	40%	3%
Aerodynamics	4%	100%	4%
Tag Axles	3%	62%	2%
CVT	10%	10%	1%
TOTAL	45%	--	28%

*In practice an optimized combination of engine fuel and speed derating would be used. The combined effect would be no more than 8%.

TABLE 3-43 FUEL ECONOMY IMPROVEMENT FOR CLASS VIII SYNTHESIZED VEHICLE WITH TURBOCHARGED DIESEL-LONG (INTERCITY) DRIVING MODE
(five axle tractor-semi-trailer, tractor-semi-trailer with full trailer)

Improvement	Vehicle Fuel Economy Improvement (mpg) For This Option	Estimated Production Capacity by 1980	Estimated Maximum Fuel Economy Improvement Attainable by 1980 Based on Estimated Production Capacity
Derated RPM*	8%	100%	8%*
Cooling	8%	100%	8%
Radial Tires	8%	100%	8%
Tag Axle	3%	77%	2%
Aerodynamics	7%	100%	7%
TOTAL	34%	--	33%

*In practice an optimum combination of engine fuel and speed derating would be used. The combined effect would be no more than 8%.

REFERENCES

1. 1972 Census of Transportation, U.S. Department of Commerce. A study of truck usage in the United States.

2. Vehicle Mission Simulation Program (VMS), Cummins Engine Company, Columbus, Indiana, 1974.

3. Rogowski, "Elements of Internal Combustion Engines", McGraw-Hill Book Co., 1953, Pg. 225.

4. Arthur D. Little, Report to DOT/EPA, "A Study of Technological Improvements in Automobile Fuel Consumption", DOT-TSC-627 SAE Paper 740605.

5. "Research and Development of the Honda CVCC Engine".

6. Detroit Diesel Engine Division, GM Corp., "Cooling of Detroit Diesel Engine", Engineering Bulletin No. 28.

7. James T. Shrader and W. H. Page, "Truck Noise IV-C, the Reduction of Cooling System Noise on Heavy Duty Diesel Trucks", DOT Report DOT-TST-71 22, May 1974.

8. "Handbook on Diesel Engine Noise Control", Table 2.

9. Sherwood, A. W. "Wind Tunnel Tests of Trailmobile Trailers" University of Maryland Wind Tunnel Report No. 85, College Park, Maryland, June 1953.

10. Wendsor, R. I. "Wind Tunnel Tests of Trailmobile Trailers, 2nd Series" University of Maryland Wind Tunnel Report No. 98, College Park, Maryland, October 1953.

11. Gross, D. S. "Wind Tunnel Tests of Trailmobile Trailers, 3rd Series" University of Maryland Wind Tunnel Report No. 150, College Park, Maryland, April 1955.

12. Rudkin-Wiley Corporation brochure "Airshield: Air Drag Reducing System" Stratford, Connecticut.

13. Air Flo Company brochure, Elkhart, Indiana.

14. TESCO flyer, San Francisco, California.

15. Ritchie, D. "Beat the Built-in Headwind: And Save Dollars on Fuel" Commercial Car Journal, September 1973.

16. Private Communications, H. Volmer, Jacksonville, Florida.

REFERENCES (CONT'D)

17. Mass Emissions from Diesel Trucks Operated Over a Road Course. Final Report, EPA Contract #68-01-2113, South West Research Institute, July 1974.

18. In-Use Heavy Duty Gasoline Truck Emissions. Part I, Mass Emissions From Trucks Operated Over a Road Course. Final Report, EPA Contract EHS 70-113, South West Research Institute, February, 1973.

19. Minutes of the November 14, 1973 Public Hearing - Exhaust Emissions Standards for Heavy Duty Vehicles State of California Air Resources Board.

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16. Abstract

This Truck and Bus Panel Report is Number Seven (7) of a group of seven (7) prepared by special panels of the Task Force established under the joint chairmanship of DOT and EPA to conduct a study of the practicability of a fuel economy improvement standard of 20% for new motor vehicles produced in the 1980 time frame.

Special consideration is given in this report to the potential improvement of truck and bus fuel economy implementable by the 1980 production year. Vehicles considered in the section are those with gross vehicle weight ratings of 10,000 pounds or more. This group of vehicles presently consume an estimated 18% of all highway fuel, but the technologies and production facilities involved in efforts to improve the fuel consumption of this category of vehicles are quite different from those of the automobile.

Analyses of available data indicate fuel economy improvements for some individual trucks can be as great as 41% by the 1980 production year. Assessment of such technology applied without cost or production capacity restraint would yield an aggregate reduction of 25% in the fuel consumed by the new trucks and buses manufactured in 1980

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